



Safe, High Power / Voltage Battery Module Design Challenges

By

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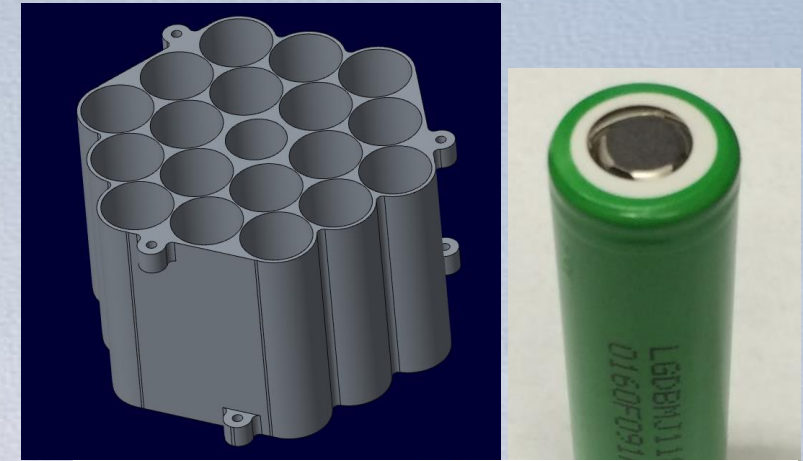
**Battery Show Europe
Stuttgart, Germany
7-9 May 2019**

Outline

- Goals of Safe, High Power Battery Task
- Major Challenges Driving Designs
 - Thermal management – Interstitial Al heat sink
 - Cell design selection for 3C discharge
 - Performance analysis on heat sink spine approach
 - Impact of epoxy, contact area, and conductivity of spine
 - Oscillating heat pipe spine
 - Risk of side wall breaches
- Summary

Safe, High Power Battery Task Top Level Reqts

- 100V, 2 kWh Battery Module
- Capable of 3C discharge continuous (20 minutes)
 - 100 cycles, 5 year storage life
- Capable of being connected in series and parallel as building block
- Safe
 - Resistant to single cell TR propagation
 - No flames exiting the module enclosure
 - Dead-face power connectors for electrocution hazard mitigation
 - Resistant to corona discharge hazard
- High performance (>160 Wh/kg, 200 Wh/L)
 - Using Li-ion commercial cylindrical cell technology that achieves 225 Wh/kg, 650 Wh/L at 3C



Latest High Power/Energy 18650 Cell Designs

- Specific Energy Range 259-276 Wh/kg
- Energy Density Range 704-735 Wh/L



Panasonic NCR18650GA

LG INR18650 MJ1



Samsung INR18650-35E

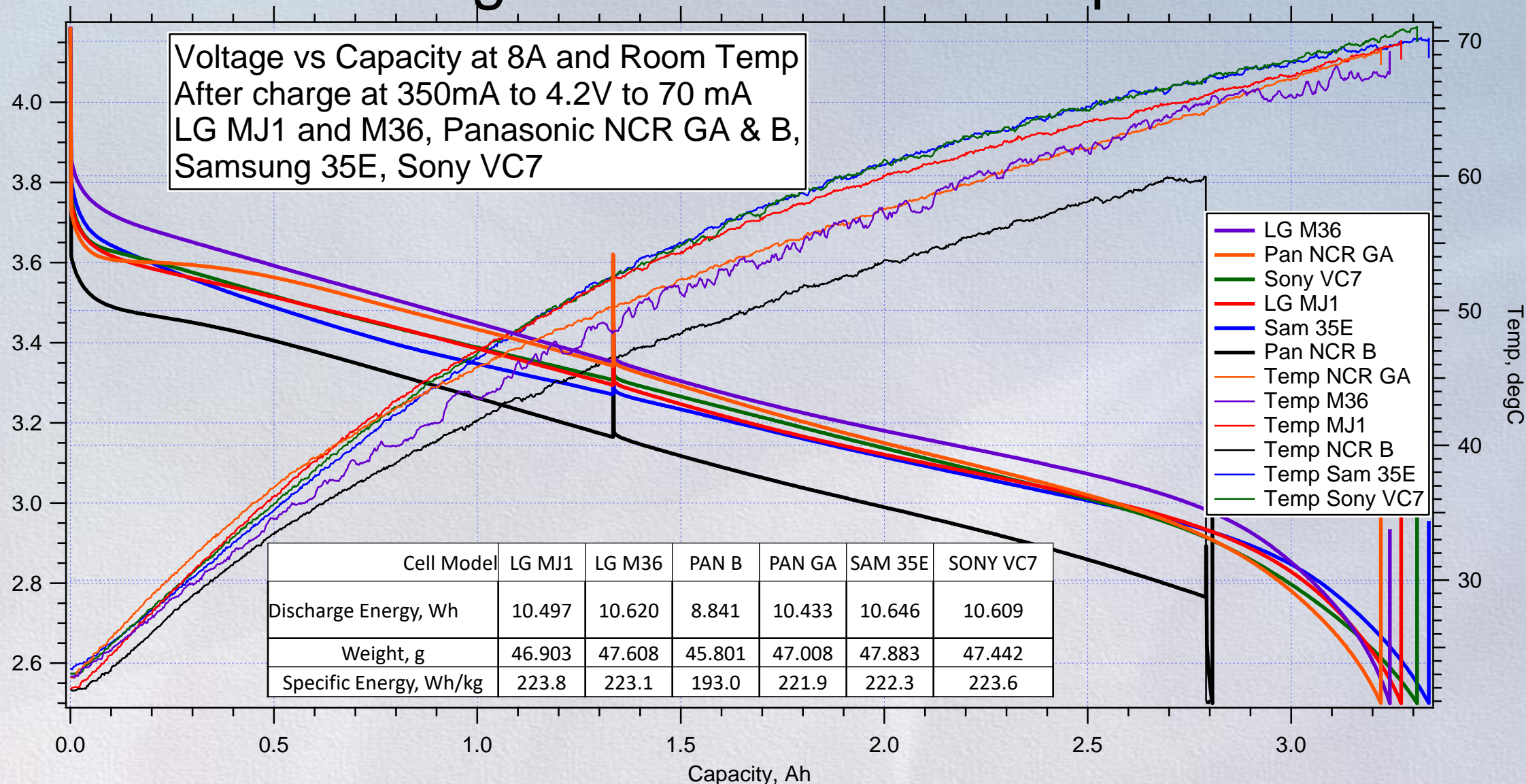


Sony US18650VC7



| C/10 at RT | Panasonic NCR GA | Samsung 3.5E | Sony VC7 | LG MJ1 |
|-------------------------------|---------------------|-----------------|-------------|--------|
| Discharge Capacity (Ah) | 3.34 | 3.49 | 3.5 | 3.41 |
| Discharge Energy (Wh) | 12.16 | 12.7 | 12.72 | 12.46 |
| DC Internal Resistance (mohm) | 38 | 35 | 31 | 33 |
| Average Mass (g) | 47 | 46 | 47.4 | 46.9 |
| Average Volume (L) | 0.0173 | 0.0173 | 0.0173 | 0.0173 |
| Specific Energy (Wh/kg) | 259 | 276 | 269 | 266 |
| Energy Density (Wh/L) | 704 | 733 | 735 | 720 |

~3C Discharge Performance Comparison



Panasonic NCR18650B has a current limiting PTC switch, adding ~10 mohms to cell resistance and trips
Note cell skins temp reaching 70°C and specific energy drops to ~223 Wh/kg

Safer, Higher Performing Spacesuit Battery Design

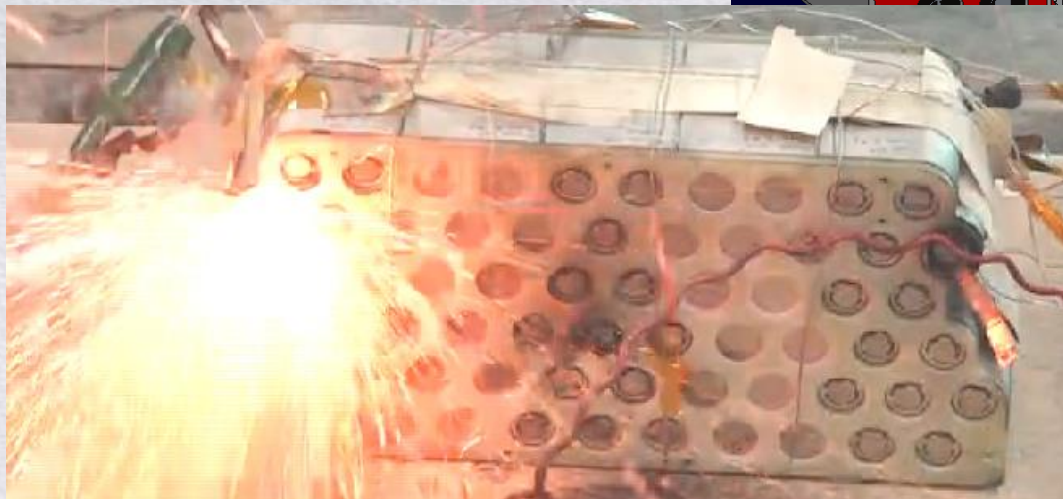
Features

- 65 High Specific Energy Cell Design 3.4Ah (13P-5S)
- 37Ah and 686 Wh at BOL (in 16-20.5V window)
- Cell design likely to side wall rupture, but supported



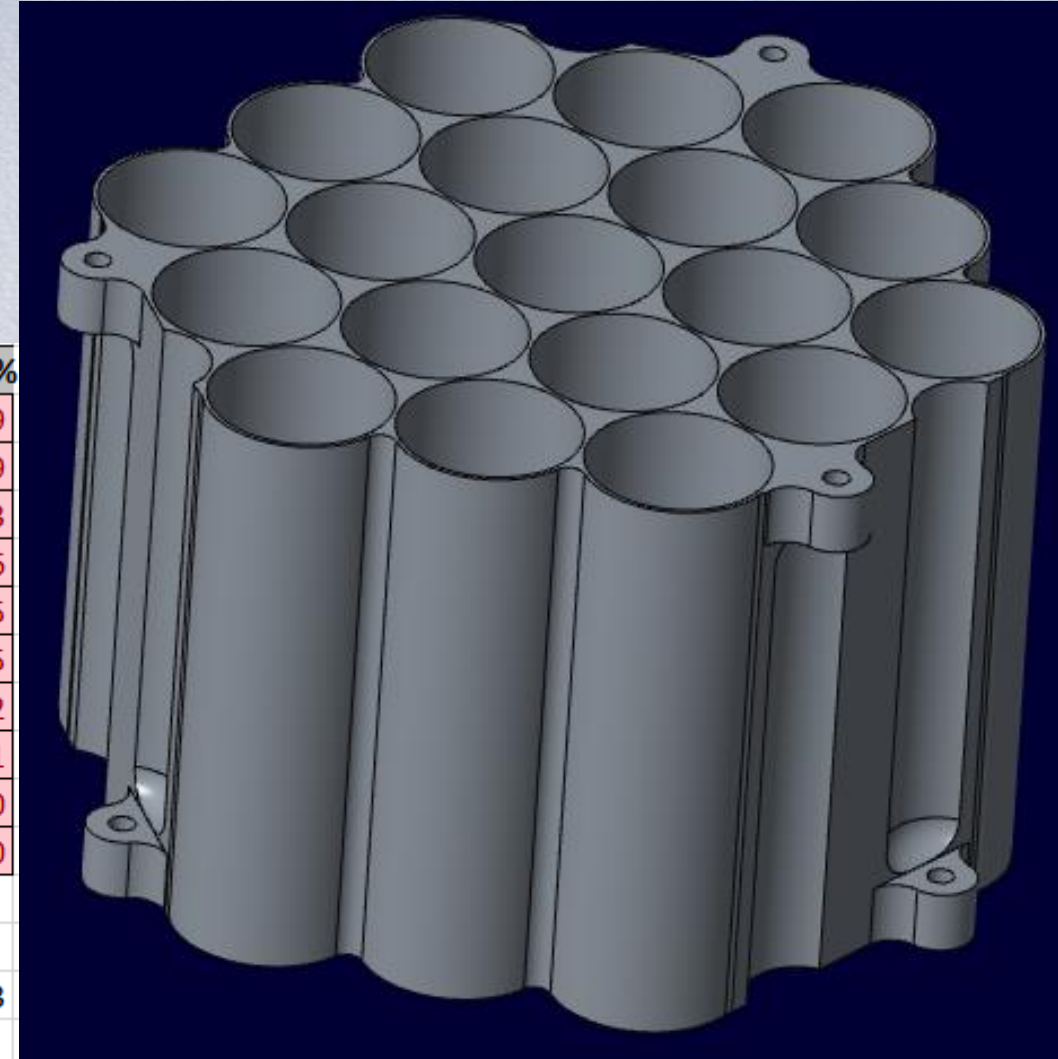
Aluminum interstitial heat sink protects adjacent cells from side wall ruptures during TR and dissipates heat very effectively

65-Battery Brick



Aluminum Interstitial Heat Sink

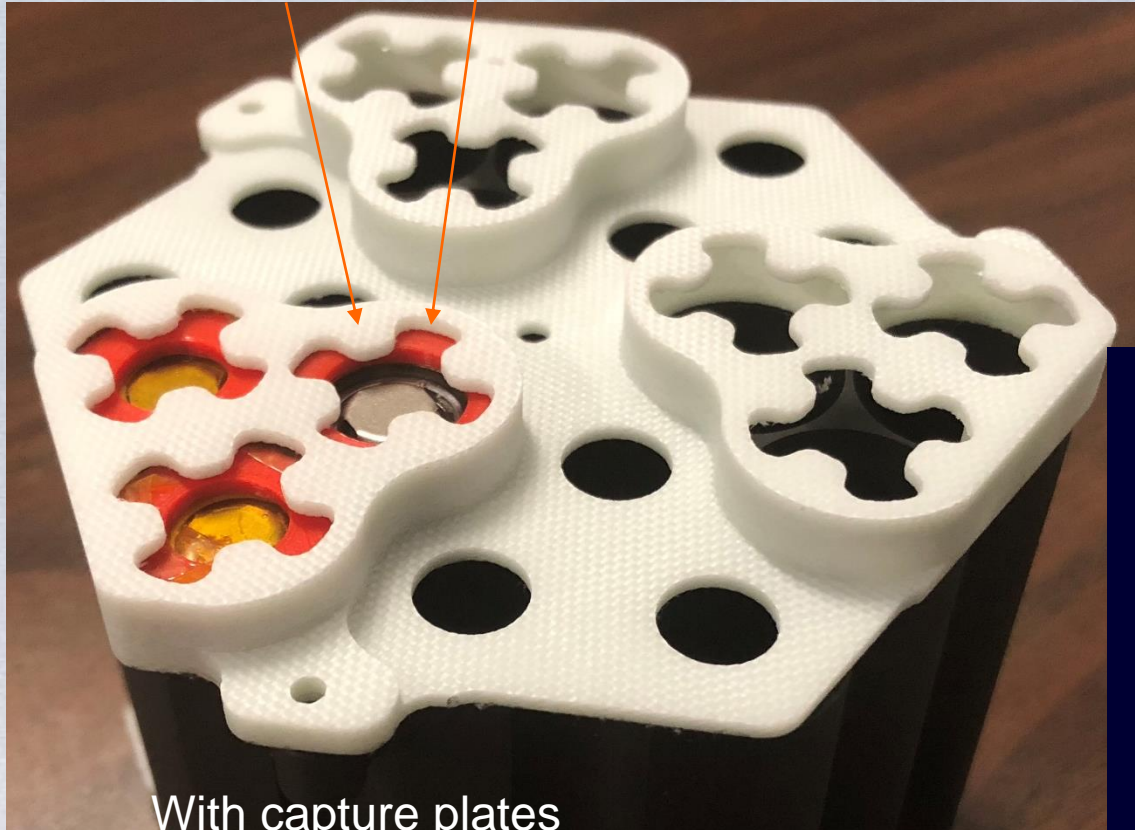
- With wire EDM, intercell webbing can be narrowed to $250\mu\text{m} \pm 25\mu\text{m}$
- All surfaces hard anodized for electrical isolation
- Provides for heat transfer & protects adjacent cells from breaches, except for spin groove area



| Part | Volume (in^3) | volume (cm^3) | mass (g) | QTY | total mass | Mass frac (%) |
|----------------|---------------|---------------|----------|------------|------------|---------------|
| Cell | 1.01100 | 16.567 | 46.00 | 18 | 828.00 | 79.59 |
| Heatsink | 3.13800 | 51.423 | 139.36 | 1 | 139.36 | 13.39 |
| Top Cap plate | 0.75300 | 12.339 | 22.21 | 1 | 22.21 | 2.13 |
| bot cap plate | 0.76200 | 12.487 | 22.48 | 1 | 22.48 | 2.16 |
| steel sleeve | 0.00601 | 0.098 | 0.78 | 18 | 14.00 | 1.35 |
| fasteners | 0.00598 | 0.098 | 0.77 | 6 | 4.64 | 0.45 |
| mica wrap | 0.00524 | 0.086 | 0.18 | 18 | 3.32 | 0.32 |
| plastic button | 0.01869 | 0.306 | 0.35 | 18 | 6.34 | 0.61 |
| paraxylene | | | | | 0.00 | 0.00 |
| bus plates | | | | | 0.00 | 0.00 |
| | | | | | | |
| | | | | Total Volu | Total mass | wh/kg |
| | | | | 383.881 | 1040.35592 | 179.07333 |
| | | | | paras Vol | Paras Mass | |
| | | | | 27.57822 | 20.41 | |

18-Cell Subscale Assembly

Breakable tabs and washer



With capture plates

- 3-cell groups offset (raise) to minimize # of adjacent spin grooves

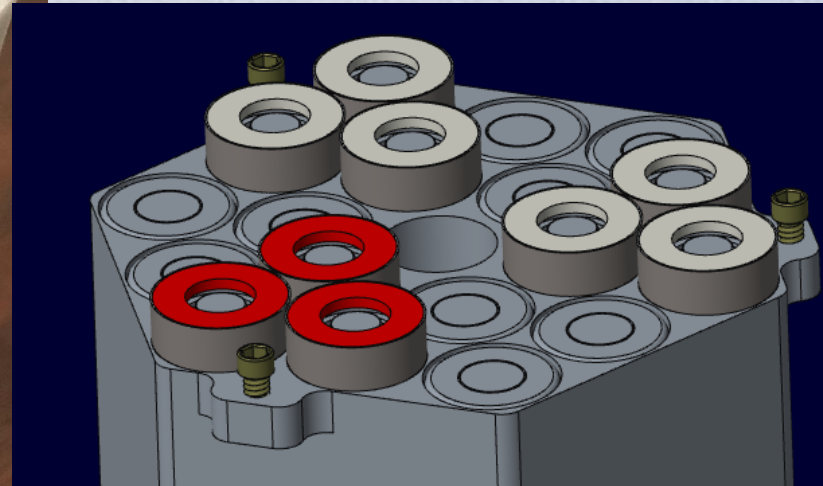
Steel Rings



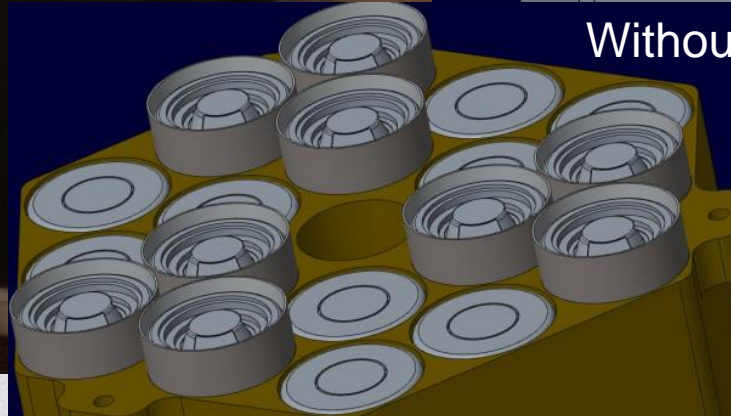
18.33mm ID
0.125mm thick
0.39g

vs

Full length
60mm tube
weighs 3.2g



Without capture plates





Bursting: Top



Bursting: Bottom



Breach: Top



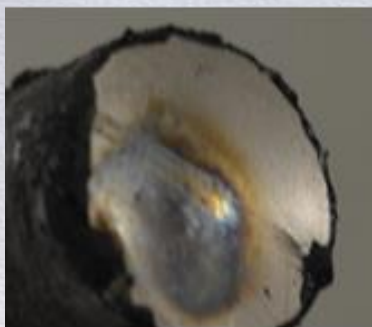
Breach: Side



Breach: Bottom

Types of Cell Enclosure Failures and Damage Conditions

Spin groove breach



Discoloration



Example of Spin Groove Breach

Cell type: Li-ion 18650

Capacity: 3.5 Ah

State of Charge: 100 % (4.2 V)

Bottom vent: No

Wall thickness: Not known

Separator: Polymer

Orientation of cell: Positive end up

Location of ISCD radially: N/A

Location of ISCD longitudinally: N/A

Side of ISCD in image: N/A

Location of FOV longitudinally: Top

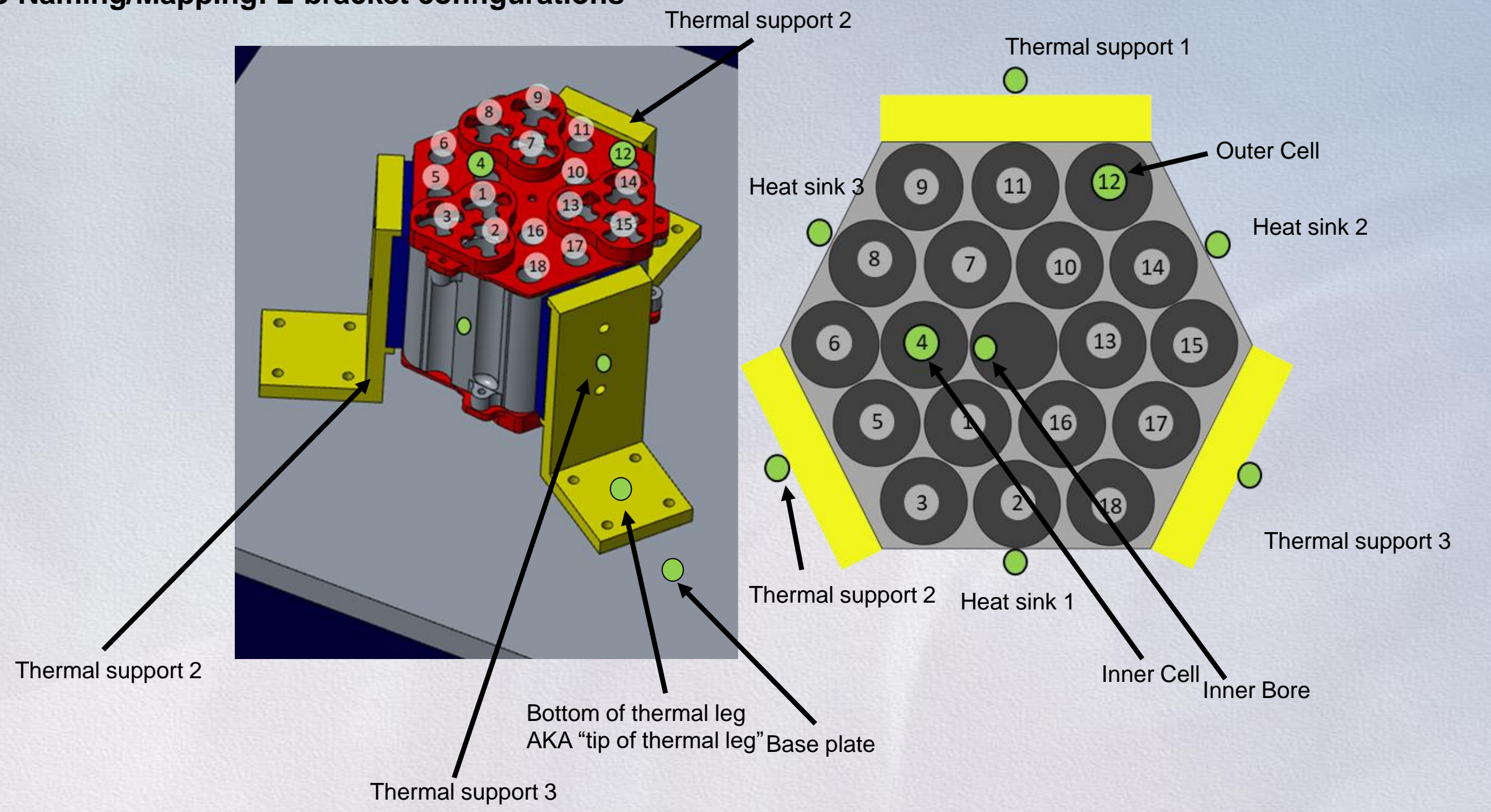
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Frame dimension (Hor x Ver): 1280 x 800 pixels

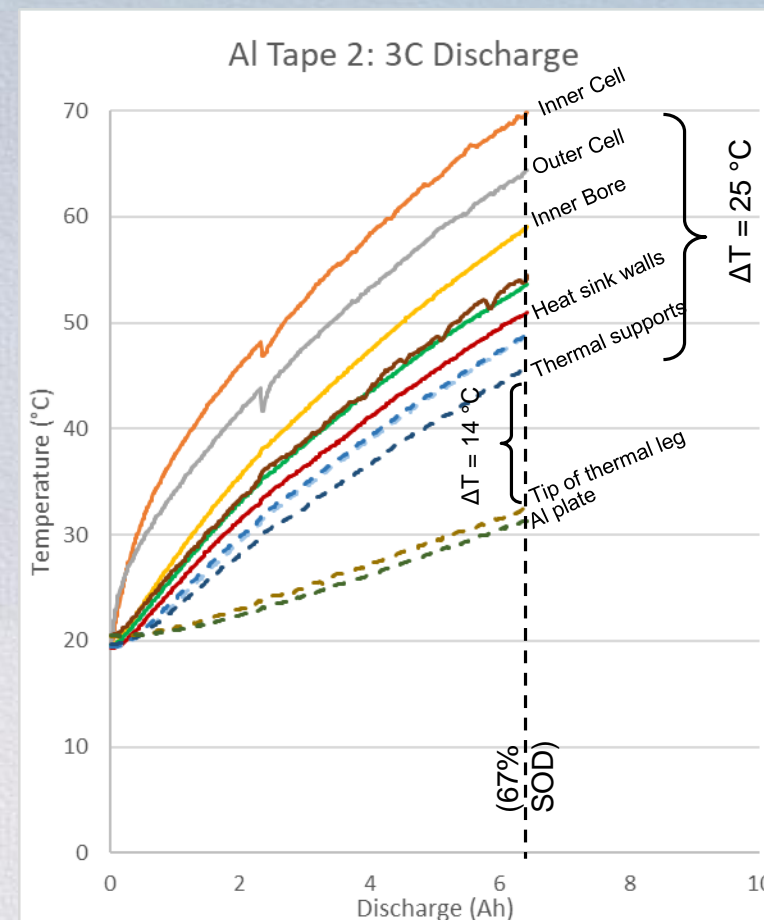
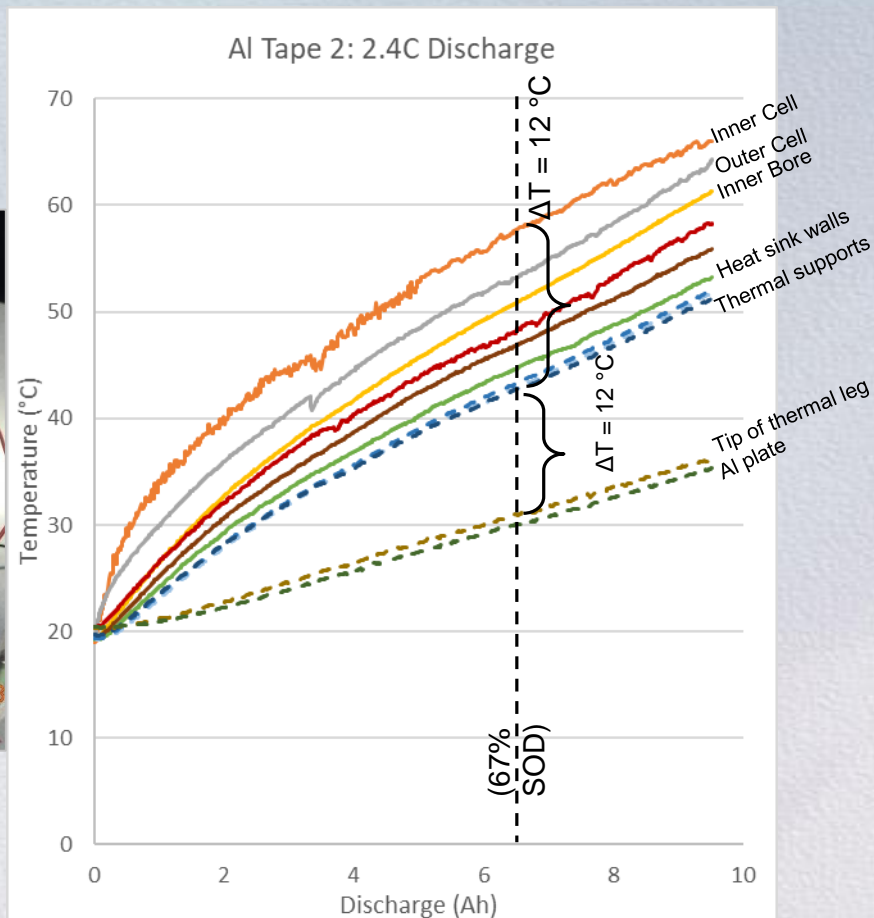
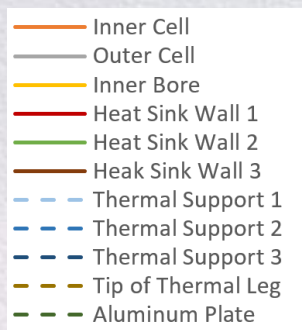
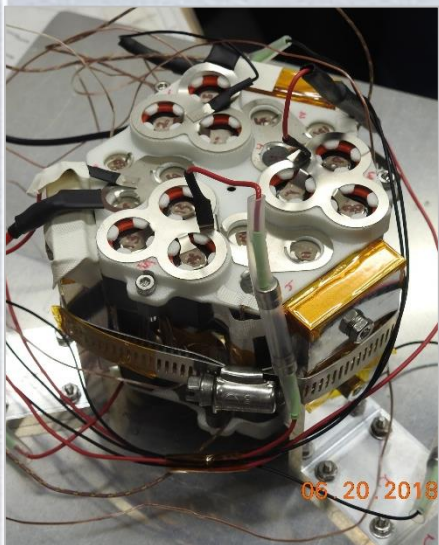
Pixel size: 17.8 μm

Credit: Donal
Finegan/NREL

TC Naming/Mapping: L-bracket configurations



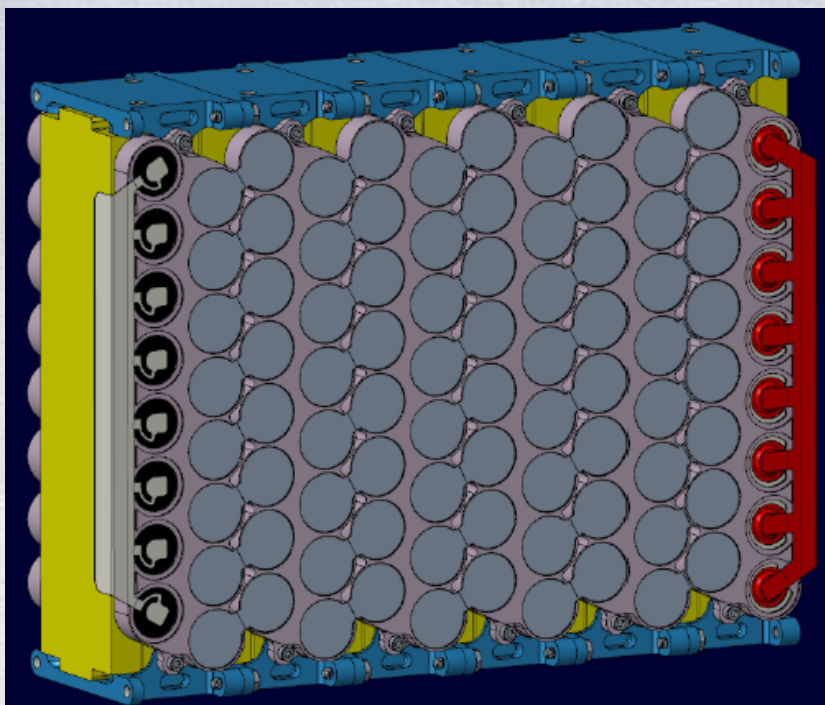
2.4C (24A) vs 3C (28.8A) discharge



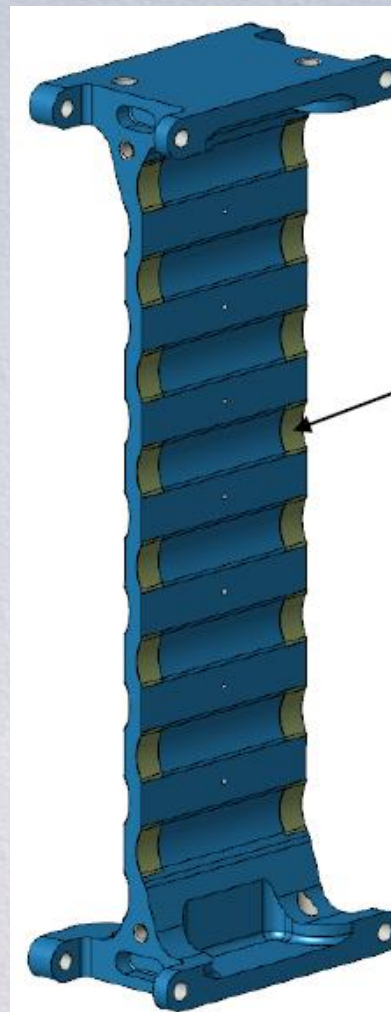
- Can't fully discharge at 3C rate before inner ring of cells reach 70°C
- ΔT between inner and outer ring of cells is alarming for 96-cell deck
- Lightweight Al interstitial heat sink with 0.5mm cell spacing is inadequate
- Need to improve heat dissipation from cells to battery housing surfaces

New Approach to Improve Heat Dissipation

- Introduce a conductive spine to heat sink each cell and insulating gaps between pairs of vertical rows of cells
 - Improve heat dissipation to top and bottom



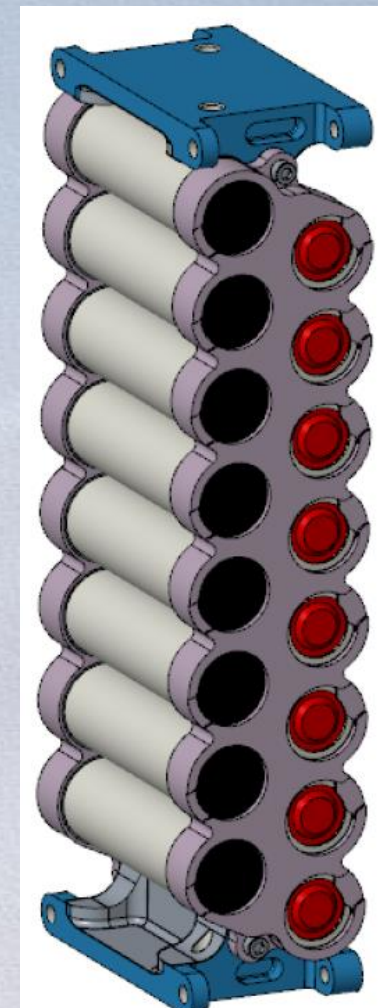
96-cell deck (1 kWh)



Al or OHP spine



G10 capture plates



16-cell assembly

How much of cell surface is needed to dissipate needed flux?

- **LG MJ1 cell with radial kapton tape at top and bottom of cylindrical wall**
 - Several winds to get 0.006" thick
 - Provide gap between can wall and heat sink block
- **Thermal paste (2-3 W/mK) bond between cell and block of Al**
 - 3/16" wide along curved cell surface
 - 0.006" at thinnest point
 - 1.5" along axial cell length
- **Insulate rest of cell with Nomex felt**
- 12AWG power wires and 4-wire sensing

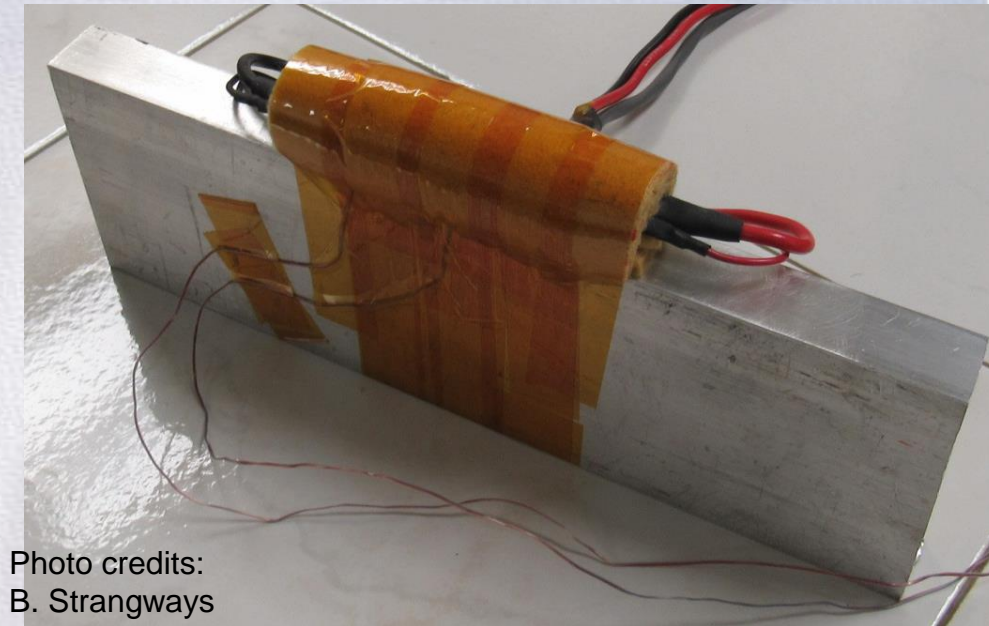
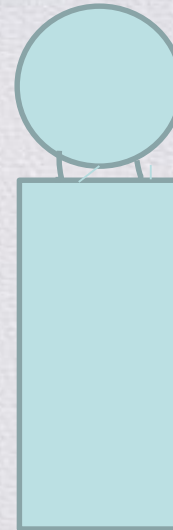
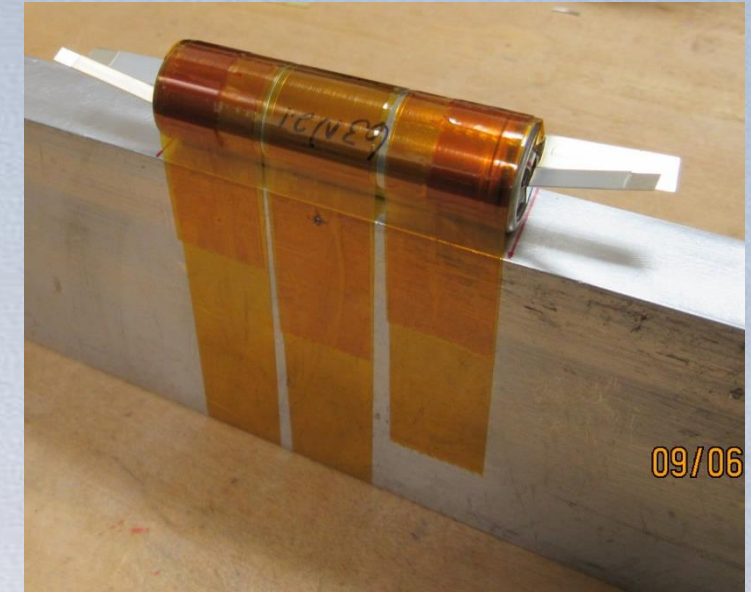


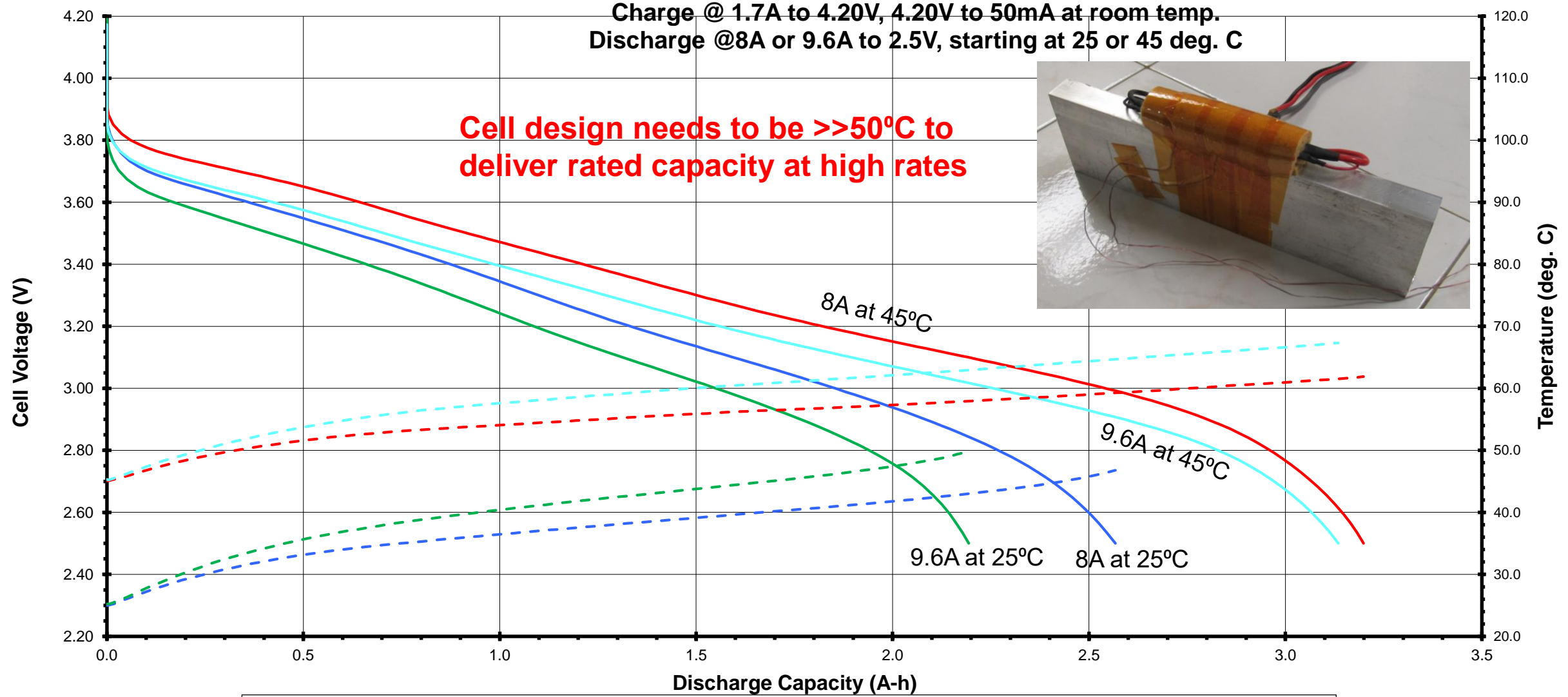
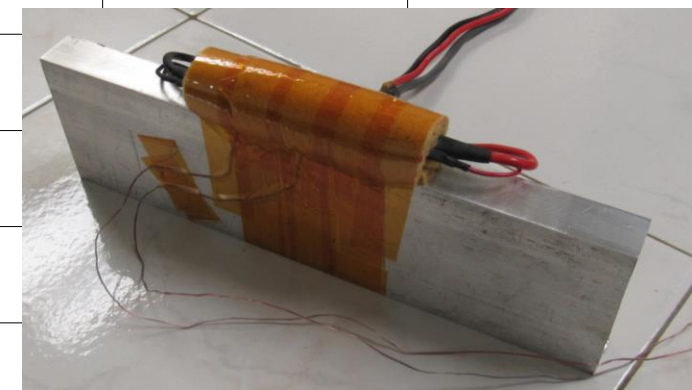
Photo credits:
B. Strangways

High Energy, High Rate Li-ion Cell Discharge Testing

LG INR18650 MJ1; Discharges With Cell Insulated and Resting on Very Large Heat Sink

Charge @ 1.7A to 4.20V, 4.20V to 50mA at room temp.
 Discharge @ 8A or 9.6A to 2.5V, starting at 25 or 45 deg. C

Cell design needs to be >>50°C to deliver rated capacity at high rates



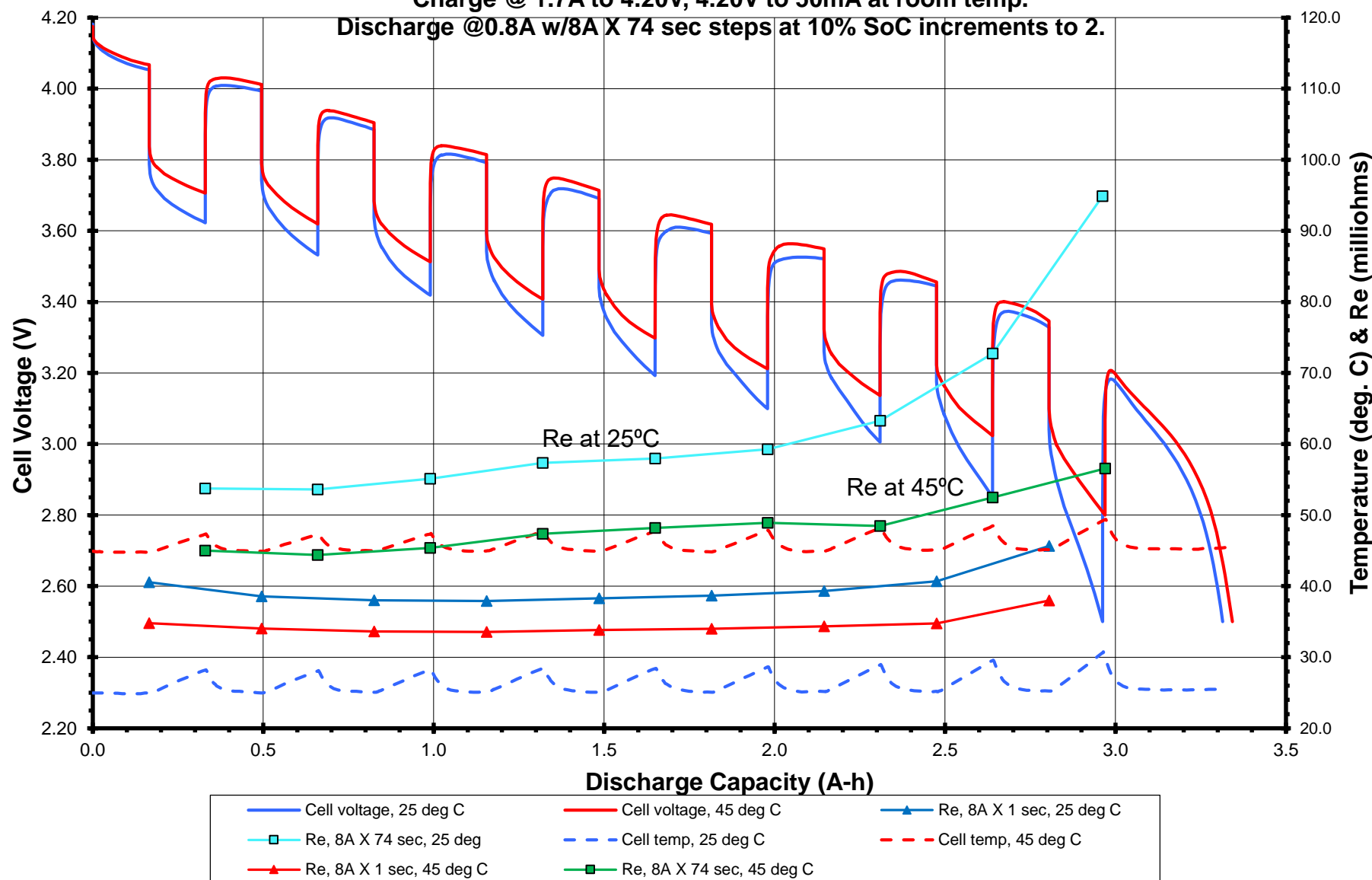
- 8A dsch volt, 25 deg C start
- 8A dsch volt, 45 deg C start
- 9.6A dsch volt, 25 deg C start
- 9.6A dsch volt, 45 deg C start
- 8A dsch Cell temp, 25 deg C start
- 8A dsch cell temp, 45 deg C start
- 9.6A dsch cell temp, 25 deg C start
- 9.6A dsch cell temp, 45 deg C start

Graph credit:
 B. Strangways

High Energy, High Rate Li-ion Cell Discharge Testing

MJ1; Discharges In Thermal Chamber With Cell Resting on Very Large Heat Sink
Charge @ 1.7A to 4.20V, 4.20V to 50mA at room temp.

Discharge @ 0.8A w/8A X 74 sec steps at 10% SoC increments to 2.



Effective Cell Internal Resistance, R_e , **significantly reduced at higher temperatures**

- R_e with 1s pulses
- R_e with 74s pulses

High Power Cell Designs: LG HG2, Samsung 30Q



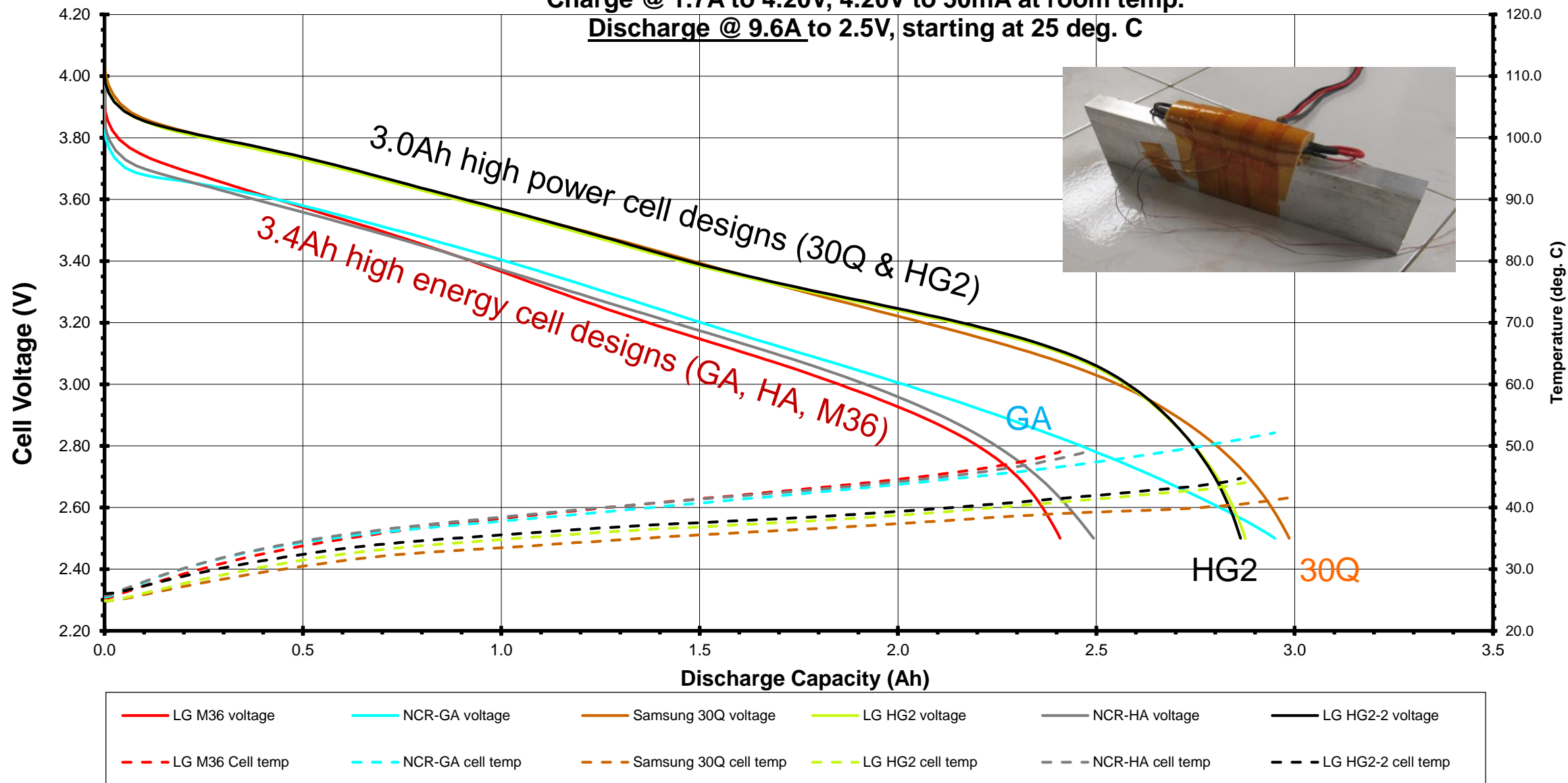
| Model 18650HG2 | | |
|--|----------|-------------------|
| Nominal Capacity*(Ah, C _N) | | 3.0 |
| Energy (Wh) | | 10.8 |
| Dimensions | Diameter | 18.3 + 0.2/-0.3mm |
| | Height | 65.2 ±0.2 mm |
| Nominal Voltage*(V) | | 3.6 |
| Internal Impedance**(mOhm) | | 14 (ave.) |
| DCIR(mOhm) | | 24 (ave.) |
| Designed charge current | | 4A |



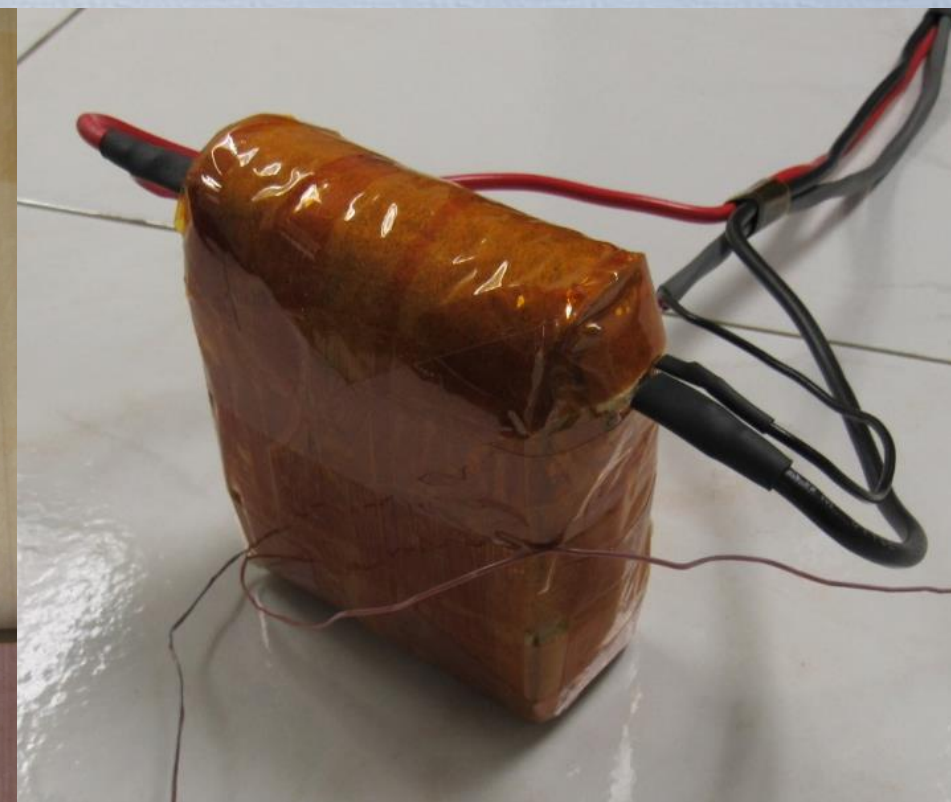
| Type | | |
|-------------------------------|------------------------|-------------------|
| Chemistry | | NCA |
| Dimension (mm) | Diameter | 18.33 ± 0.07 |
| | Height | 64.85 ± 0.15 |
| Weight (g) | | 45.6 |
| Initial IR (mΩ AC 1kHz) | | 13.13 ± 2 |
| Initial IR (mΩ DC (10A-1A)) | | 19.94 ± 2 |
| Nominal Voltage (V) | | 3.61 |
| Charge Method (100mA cut-off) | | CC-CV (4.2±0.05V) |
| Charge Time | Standard (min), 0.5C | 134min |
| | Rapid (min), 4A | 68min |
| Charge Current | Standard current (A) | 1.5 |
| | Max. current (A) | 4.0 |
| Discharge | End voltage (V) | 2.5 |
| | Max. cont. current (A) | 15 |
| rated discharge Capacity | Standard (mAh) (0.2C) | 3,040 |
| | rated (mAh) (10A) | 2,983 |

High Energy, High Power Li-ion Cell Design Discharge Testing
9.6A Discharges With Cell Insulated and Resting on Very Large Heat Sink
Charge @ 1.7A to 4.20V, 4.20V to 50mA at room temp.

Discharge @ 9.6A to 2.5V, starting at 25 deg. C



Adiabatic Cell & Al 120° Heat Sink Test



Al Block 2.0" wide X 0.75" thick X 2.28" long. There is also a small 0.04" dia hole 0.375" deep located 0.065" below the center of the nest for the Al block T/C. The nest radius provides a 120° contact. Block mass is 140.2g.

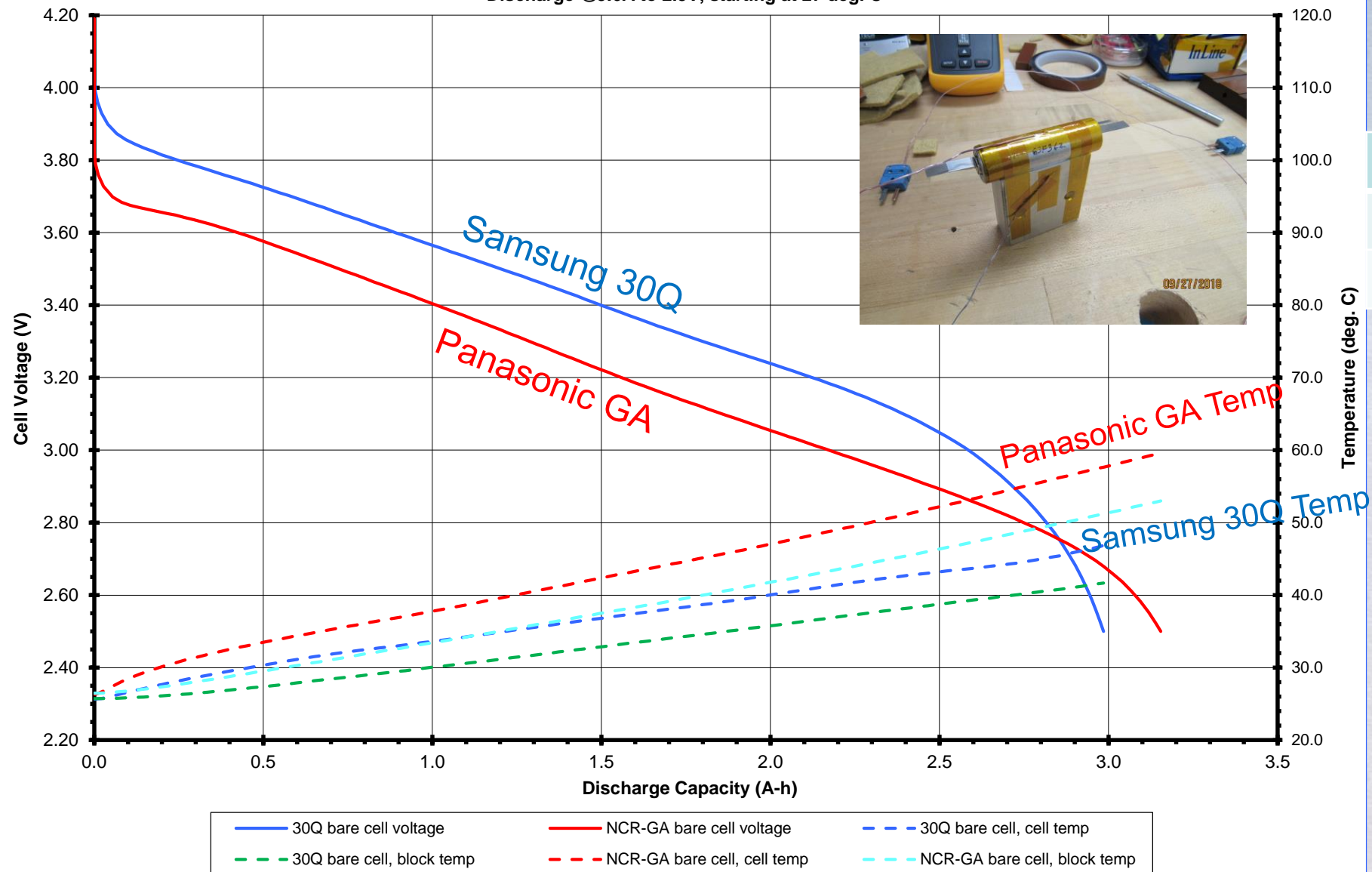
Cell to block interface = Omega thermal paste with $\kappa = 2.3\text{W/m}^2\text{K}$. Nominal film thickness is 0.003" for the mica-wrapped GA cell and 0.009" for the bare cells. The mica wrapped cell has 0.004" thk mica with 0.002" thk acrylic adhesive layer between the mica and can wall.

High Energy, High Rate Li-ion Cell Discharge Testing

Panasonic NCR18650GA vs. Samsung INR18650-30Q; Discharges in 120 deg nest Al block, fully insulated

Charge @ 1.7A to 4.20V, 4.20V to 50mA at room temp.

Discharge @9.6A to 2.5V, starting at 27 deg. C



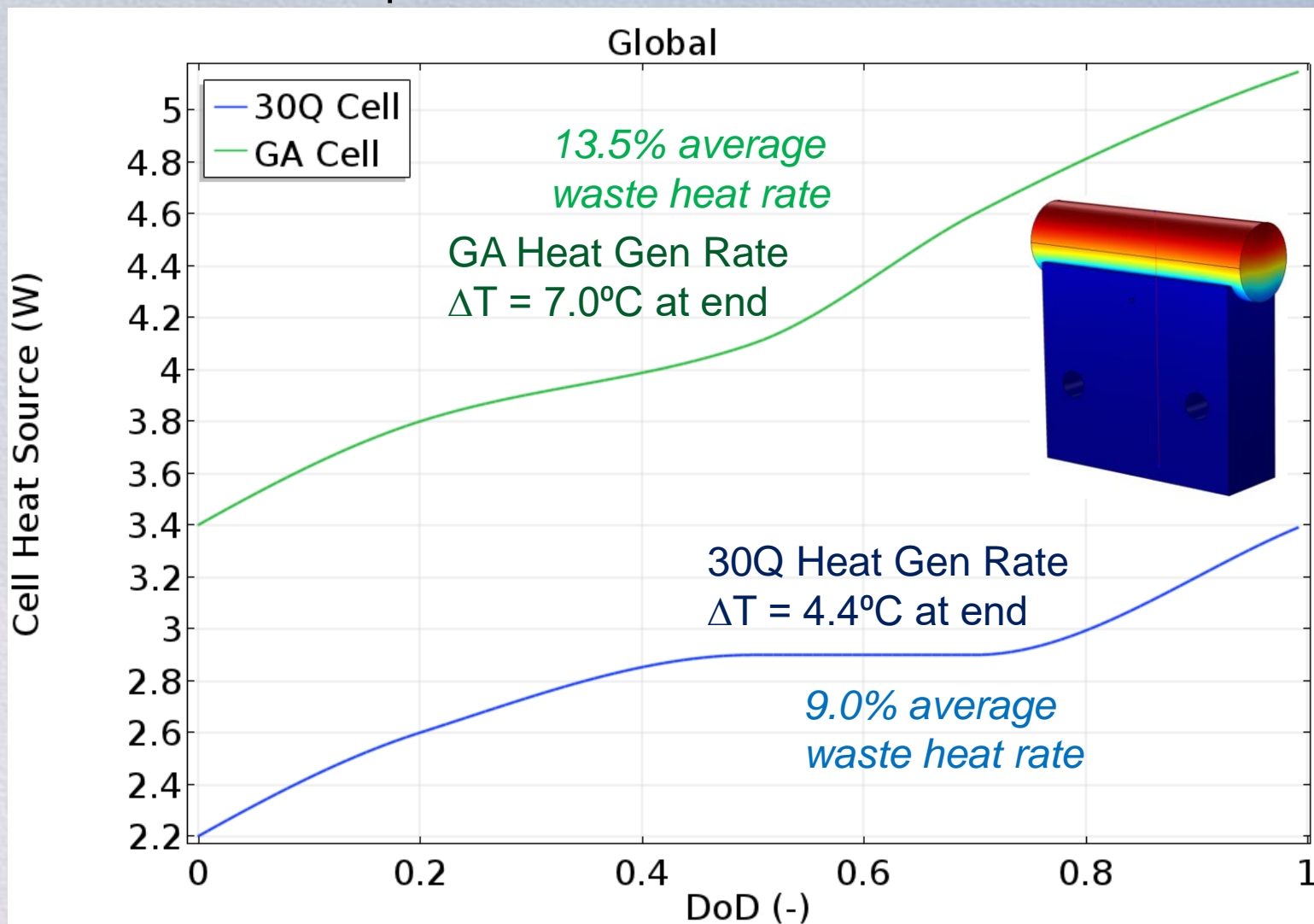
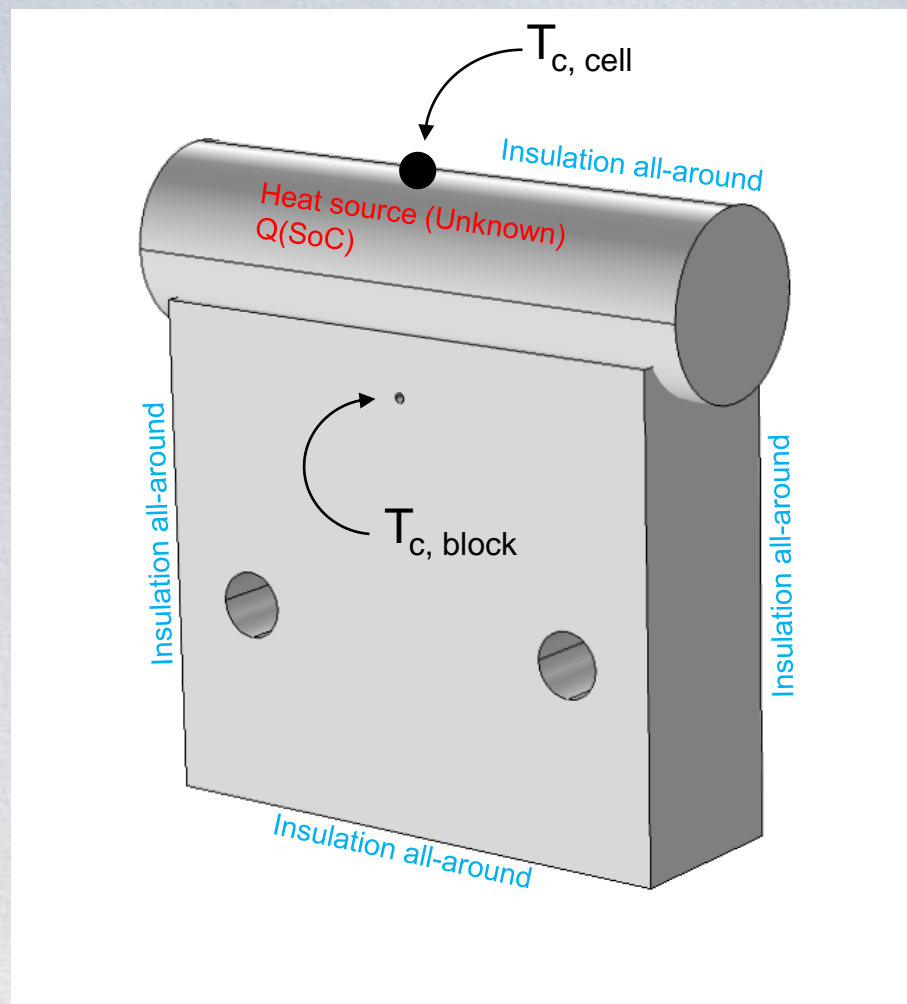
Bare cell (no mica) comparison at RT and 9.6A

| Cell Design | Ah | Wh |
|-------------|-------|-------|
| NCR GA | 3.154 | 10.08 |
| Sam 30Q | 3.029 | 10.73 |

At > 3C, high power cell design (30Q) provides more Wh and less heat than higher capacity cell design (GA)

Analysis to Extract Cell Heat Generation Rate at 9.6A

Paul Coman & Ralph White

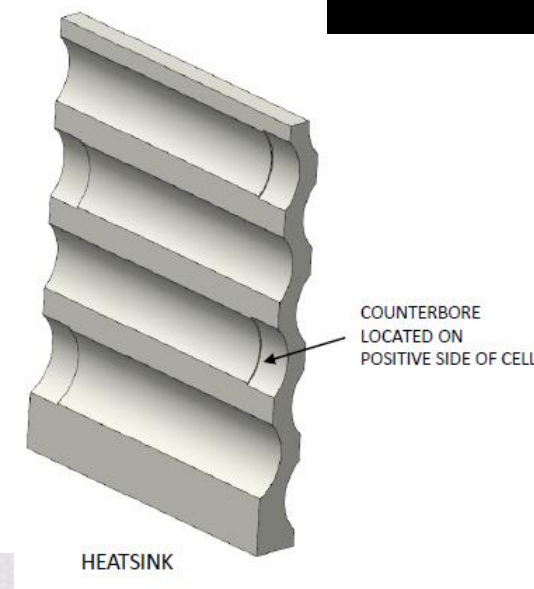
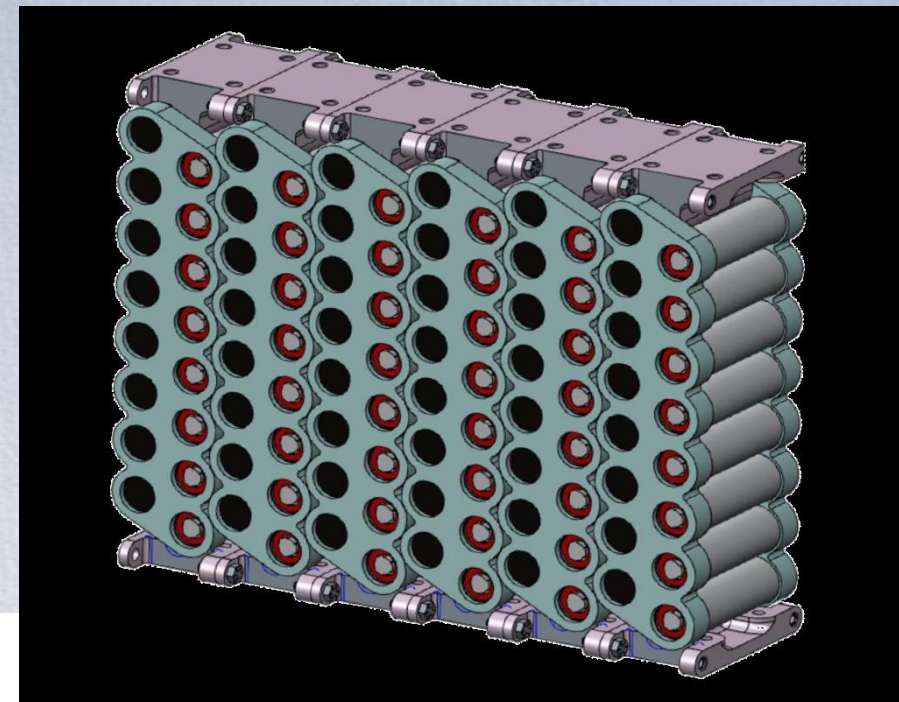
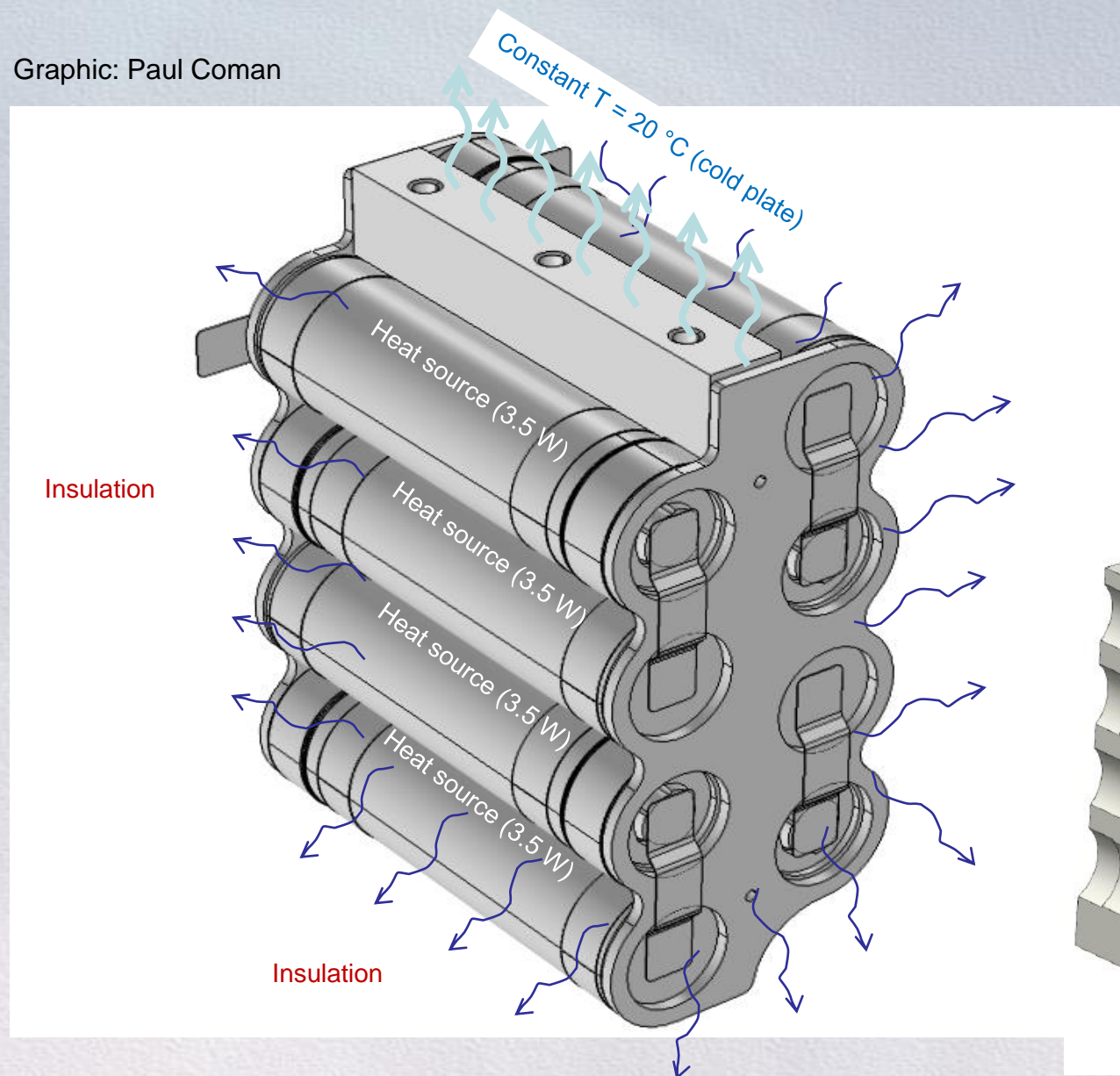


Recap of Test Findings

- Thin webbing, tight nesting heat sink with circumferential cylindrical interface with cells provides inadequate heat rejection path at 3C rates
 - *Even with the best thermal bond between cell and heat sink*
- If we improve the heat dissipation path too much and keep cells < 50°C, cell high rate performance of high energy cell designs will suffer greatly
 - *Confirmed on MJ1, M36, VC7, GA, and 35E*
- However, temperature impact on 3C performance is much less with higher power cell designs
 - *Confirmed on 30Q and HG2*
- If cell has short path to heat sink, only small amount of cell surface area is needed for adequate heat dissipation
 - *This approach is more likely to prevent TR propagation*
- **We need to keep high energy cell designs in 50-70°C range to beat capacity performance of high power cell designs**
 - *However, energy deliver is nearly equivalent between 30Q and GA > 9A, 45°C*
- Regardless, battery pack design will need to minimize ΔT between cells to keep them balanced

Solid Al Thermal Path 90° interface

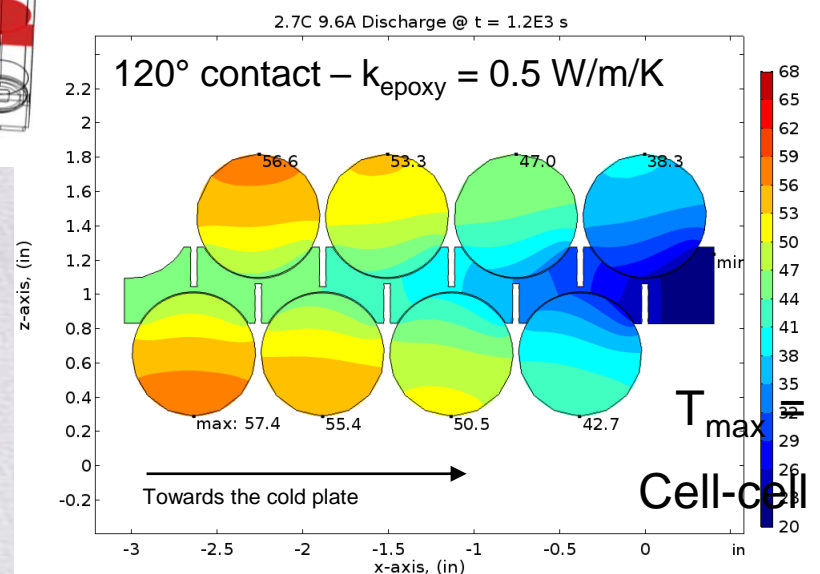
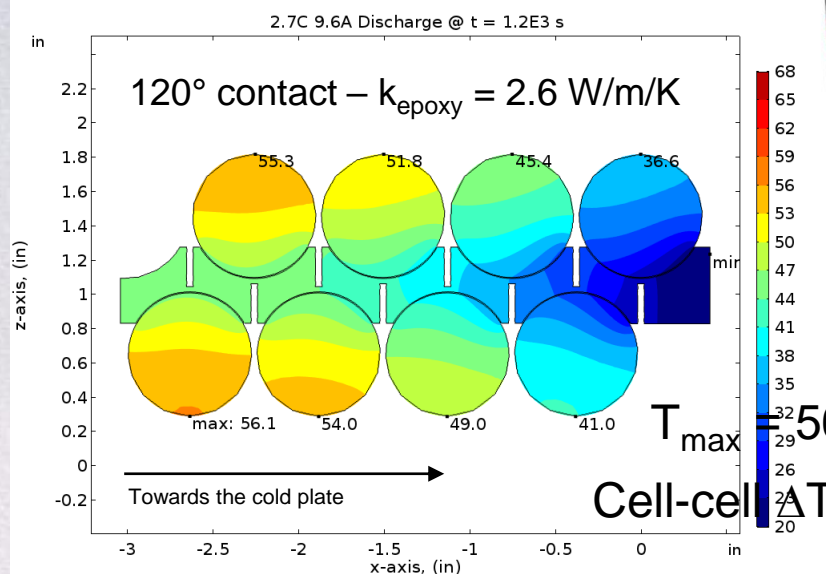
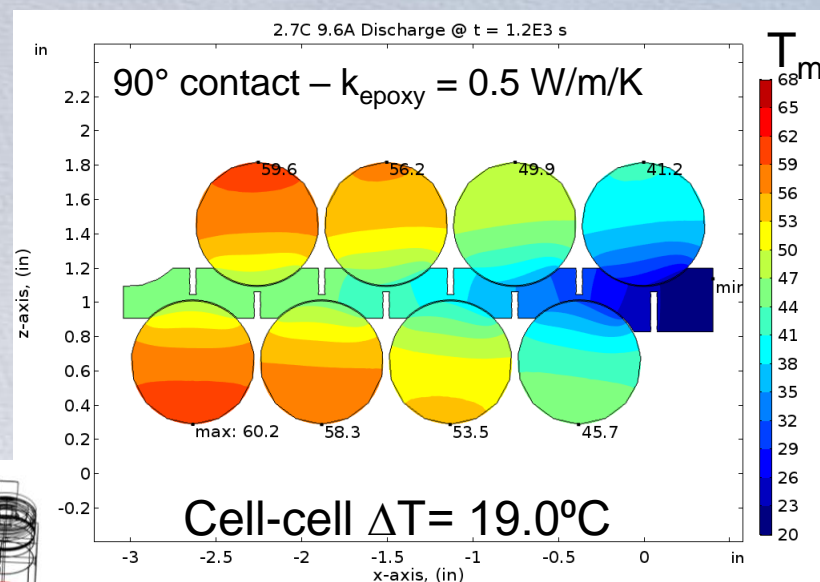
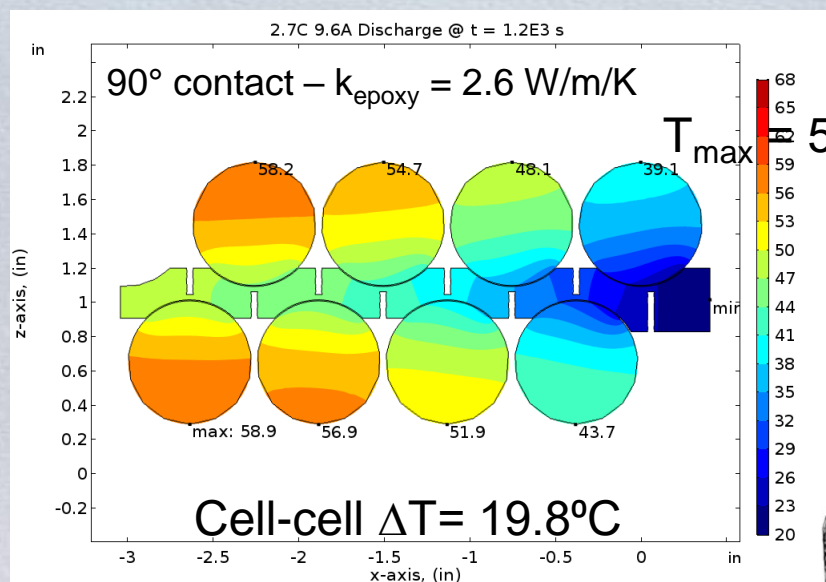
Graphic: Paul Coman



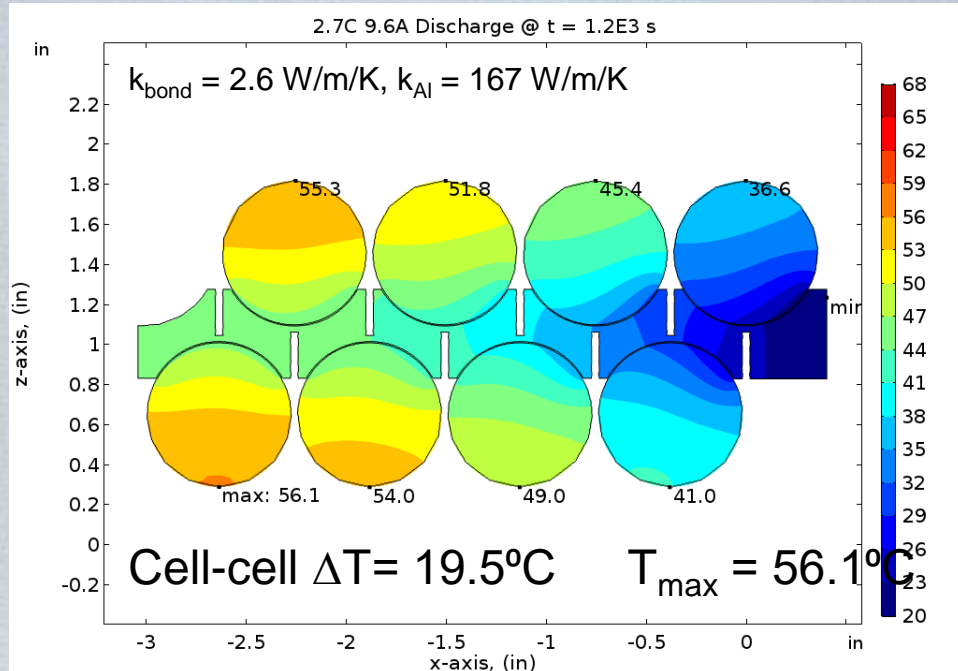
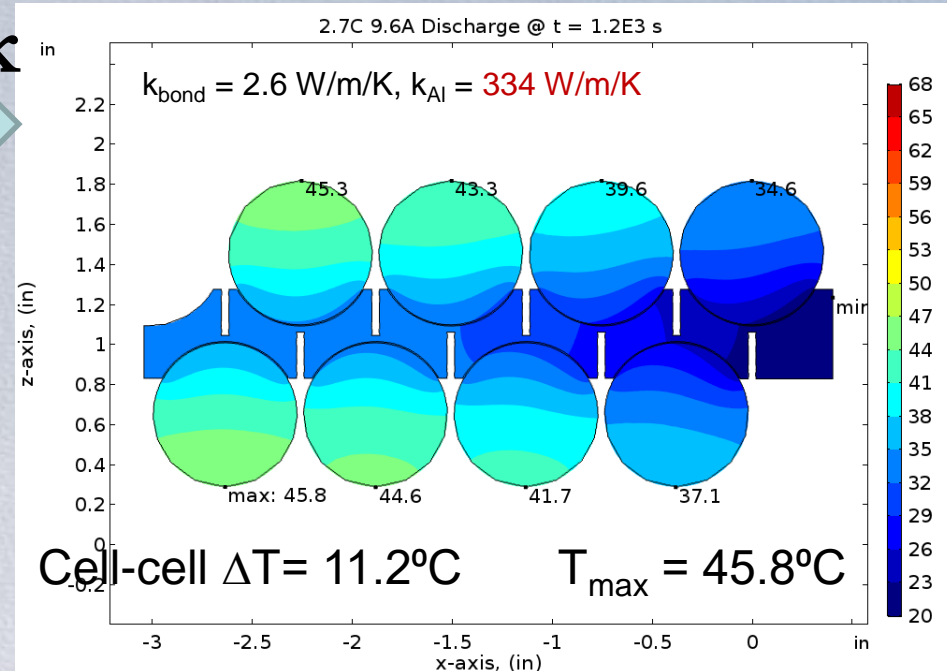
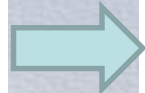
- 90° interface with cell can wall
- Epoxy bonded interface
- With interface to battery bottom plate or cold plate
- What ΔT cell to cell will we get?

ΔT differences – mid-plane cross-section

(Adiabatic case, GA cell heat gen rate – different epoxies & cell contact areas)



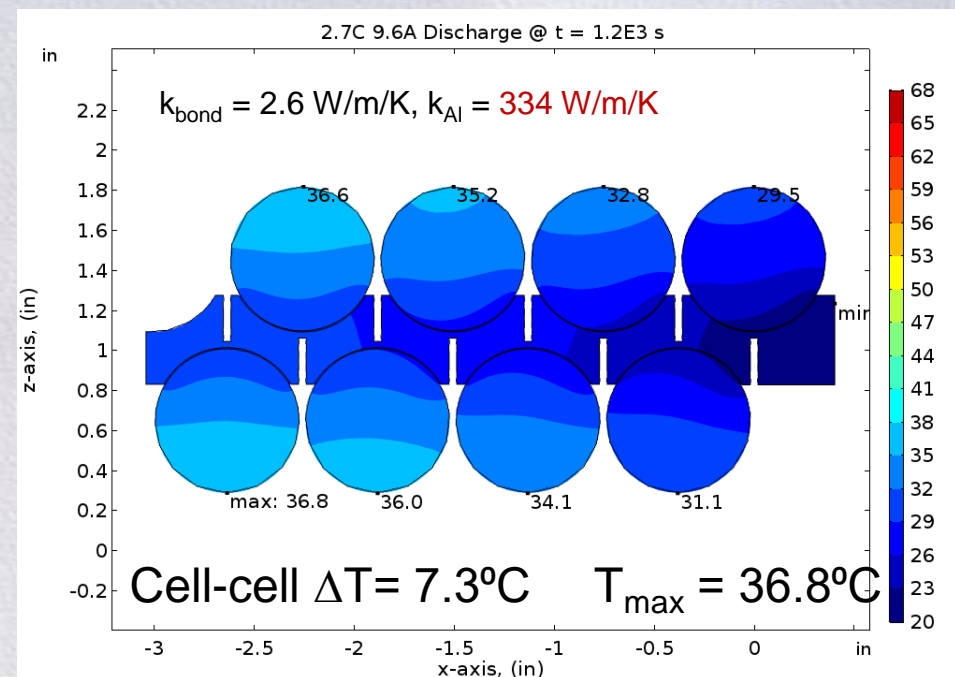
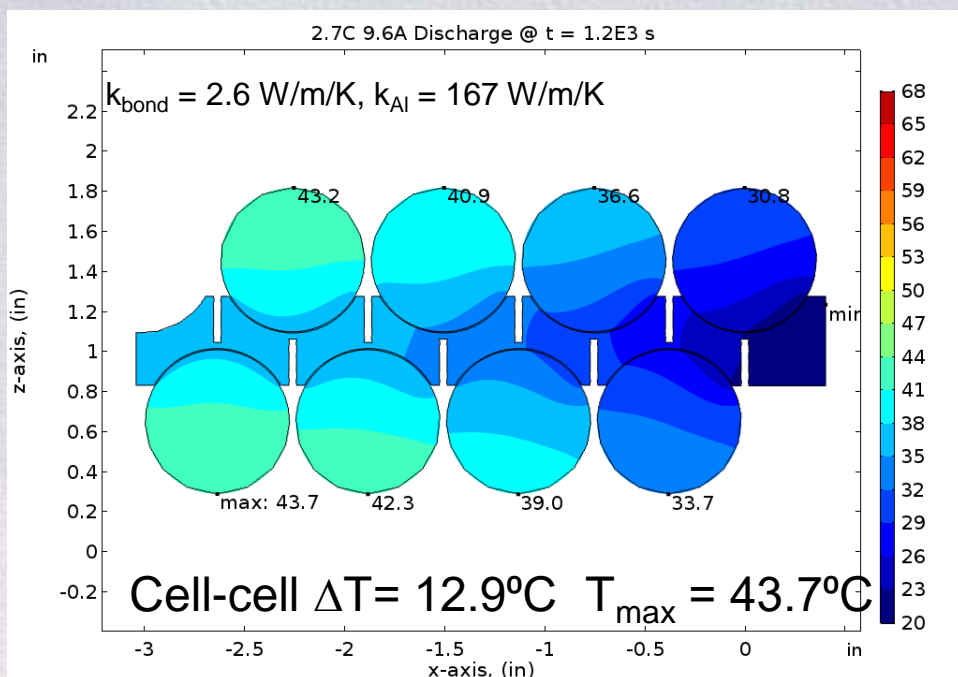
Improving thermal conductivity of epoxy or cell contact area provides little impact to cell-cell ΔT or T_{max}

2x κ 

GA



30Q



- Doubling thermal conductivity of spine reduces ΔT by 43%
- Replacing GA with 30Q cell design reduces ΔT by 33%
- Very significant improvements in both cases

Recap of Analysis Findings

Insignificant design factors

- Thermal conductivity of epoxy for cell bond
- Cell to heat sink interface area

Significant design factors

- Thermal conductivity of heat sink spine
- Reducing cell heat generation

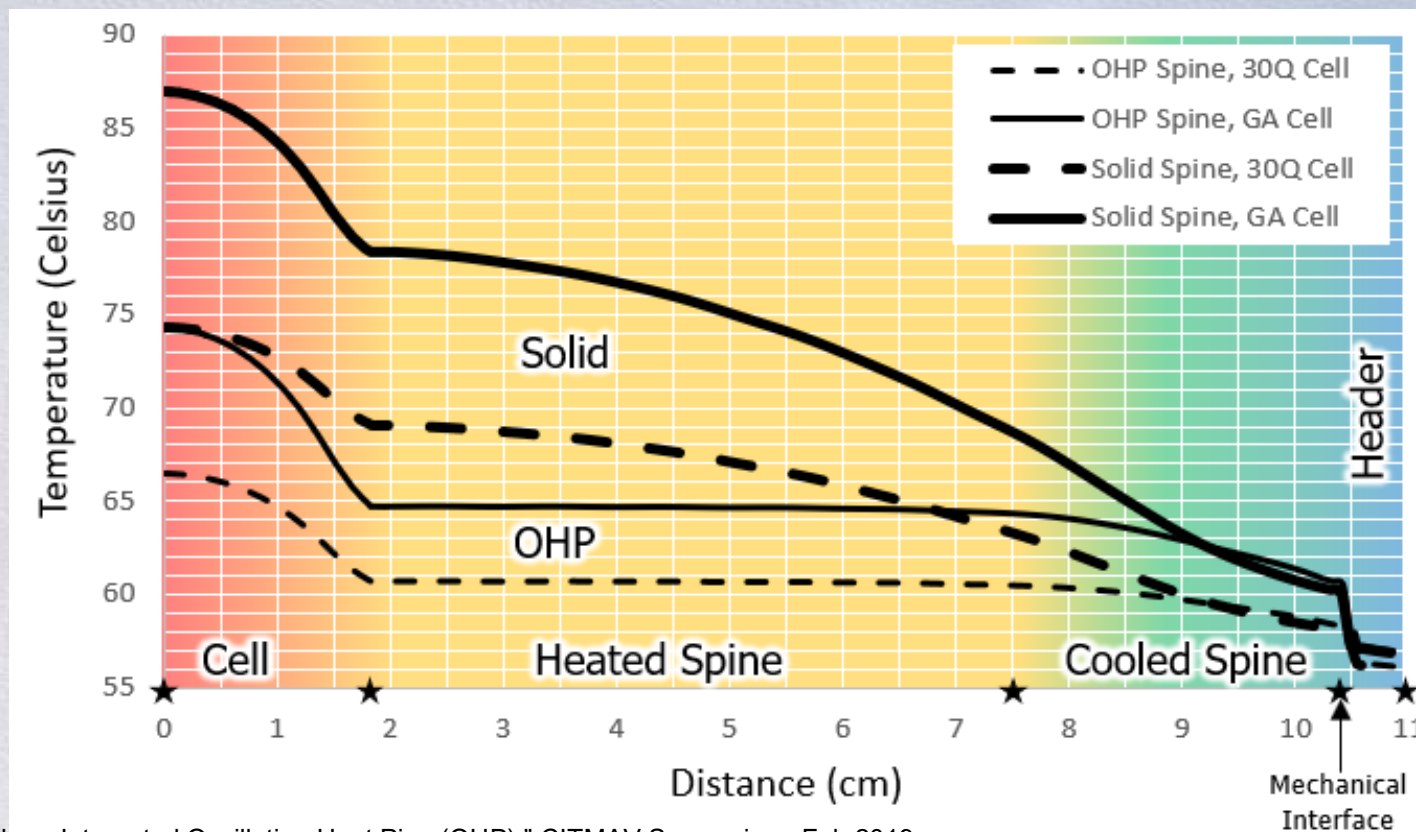
How to improve κ of heat sink spine

- ***Oscillating heat pipes***

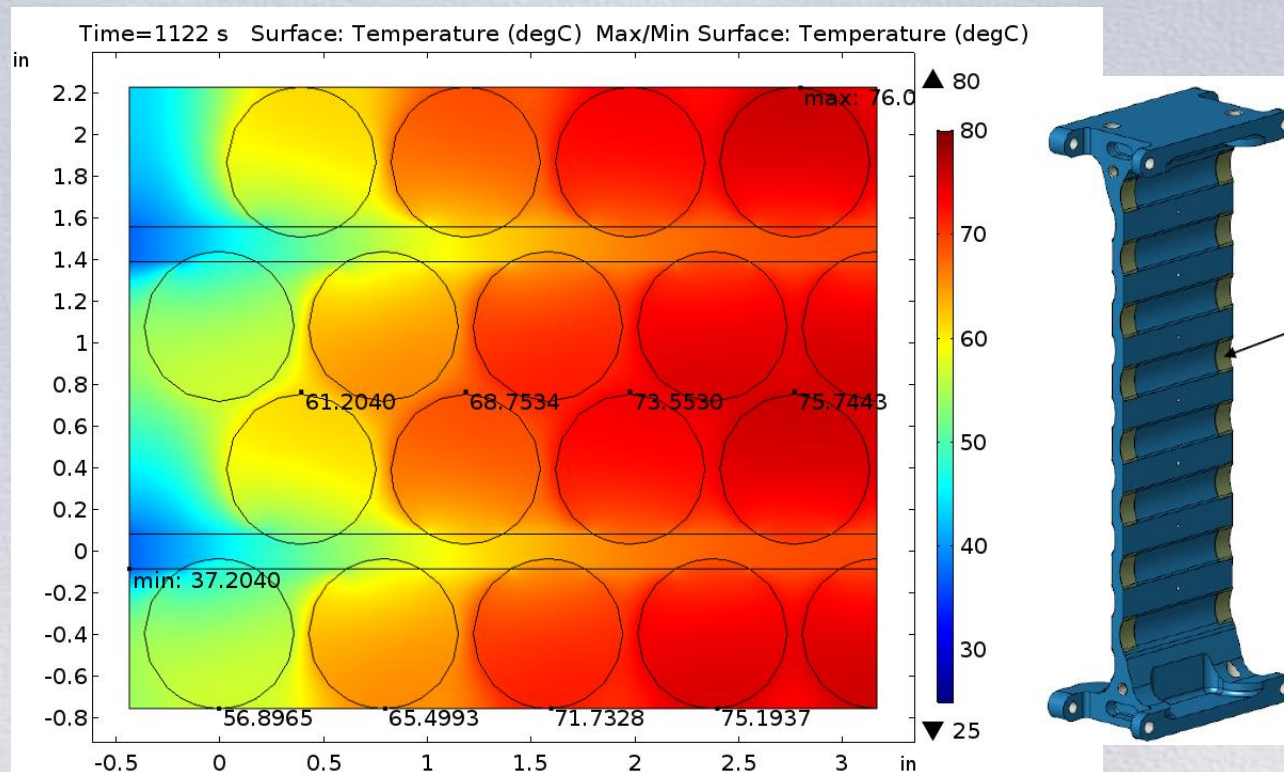


Oscillating Heat Pipes

- Heat transfer fluid encapsulated in microchannels
- Very efficient, high flux heat transfer from hot middle to cooled ends of pipe
- Greatly reduces ΔT between cells vs solid Al spines
- Significantly expands range of initial temperature operating conditions vs solid Al spines



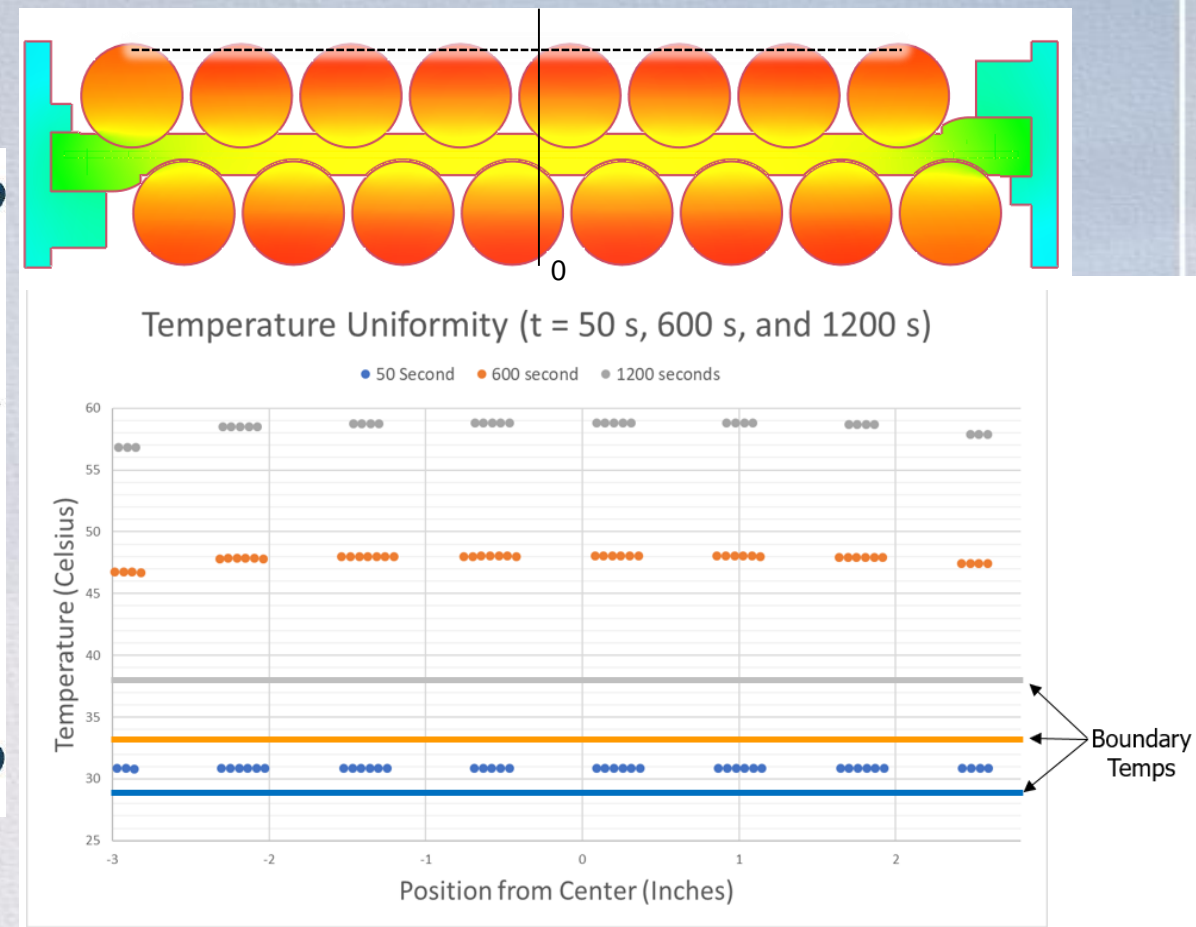
Solid AI vs OHP Spine Performance



$$T_{\max} = 76.1^{\circ}\text{C}$$

$$\Delta T_{\max} = 19.1^{\circ}\text{C}$$

Credit: P. Coman, White & Associates



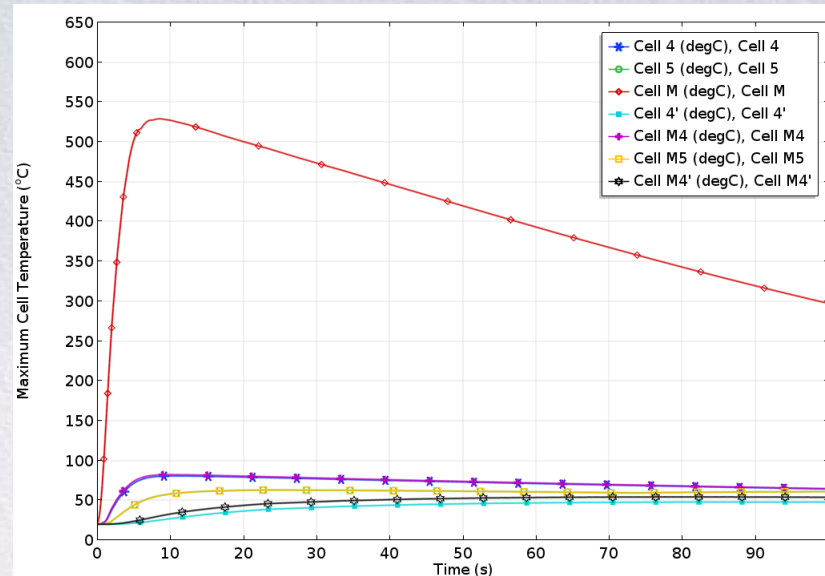
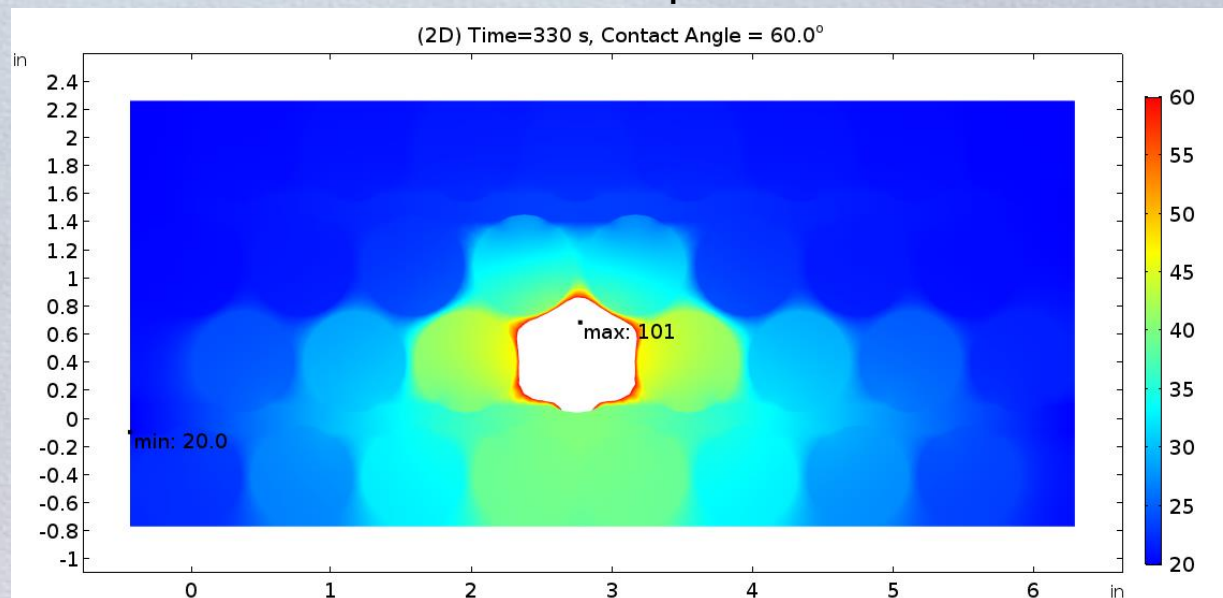
$$T_{\max} = 59^{\circ}\text{C}$$

$$\Delta T_{\max} = 2.0^{\circ}\text{C}$$

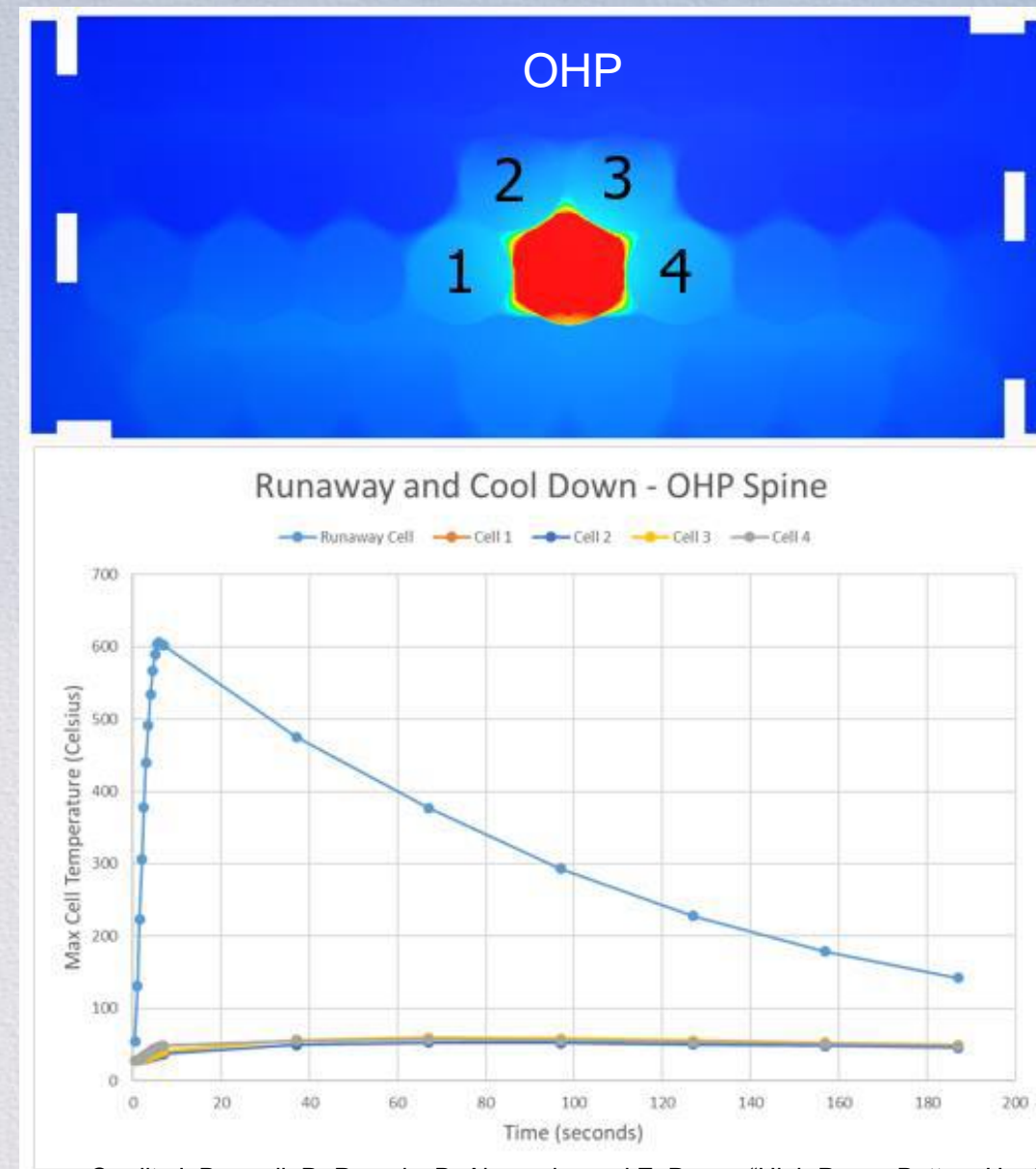
Credit: J. Boswell, D. Pounds, B. Alexander and E. Darcy, "High Power Battery Heat Sink with an Integrated Oscillating Heat Pipe (OHP)," CITMAV Symposium, Feb 2019

Both Are Predicted to Protect Adjacent Cells from Propagating TR

Solid Al Spine



Credit: P. Coman, White & Associates



Credit: J. Boswell, D. Pounds, B. Alexander and E. Darcy, "High Power Battery Heat Sink with an Integrated Oscillating Heat Pipe (OHP)," CITMAV Symposium, Feb 2019

Final Chart

- Take Away Messages

- Safe, high power battery designs that achieve > 160 Wh/kg are predicted with
 - A high performing commercial high power 18650 cell design
 - A high flux, lightweight oscillating heat pipe technology
- Verification will be complete this summer

- Acknowledgements

- C. Iannello, NASA-NESC for funding the task